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Electricity trading through both pool and bilateral markets: Integration of self-scheduling models in the MAN-REM simulation software

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To Amélinha.

Abstract

The development of the electrical sector whether in the new business model resulting from the liberalisation of a traditionally state-controlled and/or state-regulated sector or due to the deployment of new clean electricity production technologies poses big challenges. In particular, the advent of renewable energy and the massive penetration of variable renewable electricity have shaken some of the traditional pillars of the electricity sector. Despite being the symbol of a liberalised market, the pool market is a trading mechanism which induces great uncertainty on market participants' operations, becoming a considerable source of risk to the goals defined by the electricity sector's companies, particularly the goal of profit maximisation.

In this context, the first objective of this work is the extension of the multi-agent electricity market simulator (MAN-REM), developed by the Portuguese National Laboratory of Energy and Geology, allowing greater and better operation and mainly more interactivity of this software regarding the profit maximisation of generation companies through the optimisation of their portfolio's production scheduling.

After the development of a mouse and keyboard based interface which greatly facilitates the interaction with users and provides a functioning structure, three profit optimisation models were programmed and added to the software. Each of these models is characterised by its own portfolio composition, including the following technology portfolios: thermal, hydro and wind, and thermal and wind.

After the extension of the simulator with these new features, this work focused on demonstration of the optimisation models, aiming to investigate their response to different input values, namely to market prices forecasts (necessary to the self-scheduling algorithms). Additionally, a second case study was considered to use some of the initial features of MAN-REM to demonstrate the sensibility of market-clearing to higher wind production ratios.

The results of the first case study revealed a good logical coordination between the equations of each optimisation model and the output values. Furthermore, the second case study demonstrated the well-known impact of high levels of variable generation on market clearing prices.

Keywords: Self-scheduling Optimisation | Portfolio Management | Pool Market | Bilateral Contracts | Multi-agent Systems.

Resumo

A evolução do sector eléctrico, tanto ao nível do seu modelo de negócio através da liberalização de um mercado há muito controlado e/ou regulado pelos estados, quer ao nível da evolução das tecnologias de produção de energia eléctrica, apresenta grandes desafios. O advento das energias renováveis e a penetração massiva da produção de eletricidade de cariz variável vieram abalar alguns do princípios pelos quais o sector sempre se regeu.

Apesar de se assumir como o mecanismo símbolo de um regime de mercado liberalizado, o mercado em bolsa (*pool*) induz grande incerteza nas operações dos agentes que nele participam, tornando-se uma fonte de risco para os objectivos traçados por cada agente, podendo representar, em última análise, perdas não negligenciáveis que se refletem nos balanços das empresas e, por conseguinte, na sua sustentabilidade financeira a médio e longo prazo. A opção por contratos bilaterais de compra e venda de energia eléctrica, cujas condições de transação são detalhadamente definidas após negociação e acordo entre as partes, torna-se, deste modo, uma opção de mitigação do risco em que os agentes de mercado incorrem.

Nesta perspectiva, o objectivo deste trabalho é composto, numa primeira fase, pela extensão do simulador multi-agente de mercados de energia, MAN-REM, desenvolvido pelo Laboratório Nacional de Energia e Geologia (LNEG), permitindo uma maior operacionalidade e interatividade do software na sua vertente de maximização do lucro das empresas (agentes) de produção de energia eléctrica, através da optimização do agendamento de operações da sua carteira de ativos, no que respeita às infraestruturas de produção de energia eléctrica.

O plano de agendamento é calculado com base nas características técnicas de cada central, como o custo de produção fixo, custo de produção variável, custo de desligamento, custo de ligação e, no caso de centrais térmicas, custos de emissão de gases de efeito de estufa. A soma de todos estes factores (quando aplicáveis) representa, nos modelos de optimização considerados, o encargo financeiro decorrente da produção de energia eléctrica que deverá ser minorado pela colocação informada de volumes de energia no mercado, permitindo a anulação dos custos através da majoração dos proveitos. Consequentemente, as previsões de disponibilidade de produção de centrais eléctricas de cariz variável — traduzidas através de dados horários de velocidade do vento (para a geração eólica) e escorrência de águas (para a produção hídrica) — e a estimativa de preços de mercado para compra e venda de energia eléctrica, são também dados de entrada essenciais, que permitem a um produtor "prever" quais as unidades de produção rentáveis a uma determinada hora e qual a forma mais benéfica para a sua venda: o mercado em bolsa ou a contratação bilateral.

A construção de um conjunto de janelas, em linguagem JAVA, que permitam definir uma interface de apoio ao manuseamento das novas funcionalidades de agendamento, foi uma fase essencial do trabalho. As diversas janelas criadas permitem simular as funções de adição manual de novos agentes produtores — incluindo todas as características técnicas dos seus portfólios segundo as várias tecnologias de produção inerentes a cada central —, a adição de novos agentes a partir de ficheiros de dados externos (EXCEL), a optimização do agendamento da produção de um agente, a visualização de dados de saída detalhados do processo de optimização e, finalmente, a simulação de uma plataforma electrónica de casamento automático de ofertas compra e venda de energia em ambiente de transação bilateral. Adicionalmente, foram programados três modelos de optimização de lucro através do agendamento da produção de energia eléctrica, resultando num exercício de programação moderado a elevado. Os modelos contam com diferentes composições características de portfólios, tendo sido consideradas carteiras de unidades produtivas exclusivamente térmicas, hídricas e eólicas e ainda térmicas e eólicas. Os três modelos foram adicionados ao simulador já existente (MAN-REM).

Após a ampliação das funções do simulador, quer ao nível da interface, quer do código necessário para possibilitar todas as suas funcionalidades e a compatibilidade com o software já existente, este trabalho focou-se essencialmente na demonstração dos modelos de optimização da produção adicionados ao simulador, de forma a analisar a sua resposta a diferentes valores de entrada, nomeadamente às previsões de preços de mercado em bolsa (necessárias aos algoritmos de agendamento) e, assim, assegurar o seu correto funcionamento.

A formulação do primeiro caso de estudo, composto por duas simulações do mercado diário por cada exercício de validação dos modelos testados, requereu, para as vinte e quatro horas de um dado dia, a utilização de um conjunto de perfis de consumo fixos, alocados a um grupo de agentes comercializadores de energia eléctrica — retalhistas — assim como um outro conjunto de ofertas de venda de energia, proveniente de um grupo de produtores de eletricidade, de forma a dotar o mercado de uma competição significativa, tanto do lado da procura como da oferta. Para cada um dos modelos, a primeira simulação de mercado contou com a participação de todos os agentes referidos — produtores e retalhistas — e de uma oferta de venda de energia adicional proposta por um novo agente produtor (produtor-teste). Os vinte e quatro preços relativos ao custo marginal de mercado, resultantes da simulação da primeira sessão, foram então utilizados como previsões de preços do mercado *pool* do produtor-teste numa segunda sessão de mercado, na qual as suas ofertas de venda de energia eléctrica, decorrentes da sua atividade produtiva, foram sujeitas ao algoritmo de optimização a ser validado. Desta forma, a concordância de valores referentes aos volumes de energia eléctrica enviados para o mercado nas primeira e segunda sessões pelo produtor-teste, permitiram atestar o funcionamento dos algoritmos de optimização em estudo. De facto, os resultados dos testes realizados revelaram uma boa coordenação entre as funções-objectivo e as restrições lógicas e técnicas aos problemas a serem solucionados pelos três modelos em estudo, sendo os dados finais coerentes com os resultados que seriam esperados.

De forma a utilizar as novas ferramentas disponibilizadas pelo MAN-REM para a demonstração da susceptibilidade dos preços de mercado em bolsa à variabilidade intrínseca à produção de energia eléctrica de origem renovável, nomeadamente a partir do recurso eólico, e dos seus reduzidos custos marginais, foi considerado outro caso de estudo. Deste modo, e utilizando o mesmo grupo de agentes retalhistas do exercício anterior, foram considerados dois cenários antagónicos no que respeita às condições atmosféricas para produção renovável, tendo sido analisados os efeitos da maior ou menor contribuição de energia eólica sobre o preço marginal do mercado bolsista. Consequentemente, foi possível verificar o efeito de redução substancial dos preços marginais do mercado bolsista nas situações em que a produção eólica variável apresenta valores médios horários acima da média, corroborando o pressuposto teórico de que tecnologias com menores custos de produção marginal contribuem para uma maior eficiência deste mecanismo de comercialização, não só através de uma redução do custo da energia eléctrica em mercado por substituição de tecnologias mais dispendiosas, como também de um aumento do bem-estar social por efeito da majoração do volume total de energia eléctrica a ser efetivamente negociado e transacionado em mercado.

Palavras-chave: Optimização de Agendamento da Produção | Gestão de Portfolio | Mercado em Bolsa | Contratos Bilaterais | Sistemas Multi-agente.

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Acronyms

ABMS	Agent-based Modelling and Simulation
BC	Bilateral Contracts
CAPEX	Capital Expenditures
CCGT	Combined Cycle Gas Turbine
CfD's	Contracts for Differences
CHP	Combined Heat and Power
CMVM	Comissão do Mercado de Valores Mobiliários
CNE	Comisíon Nacional de Energía
CNMV	Comisíon Nacional del Mercado de Valores
CO_2	Carbon Dioxide
EDP	Energias de Portugal
ERSE	Entidade Reguladora dos Serviços Energéticos
GenCo	Generation Company
GHG	Greenhouse Gases
GW	Gigawatt
ISO	Independent System Operator
LNEG	Laboratório Nacional de Energia e Geologia
MAN-REM	Multi-Agent Negotiation and Risk Management in Electricity Markets
MAS	Multi-agent System
MCP	Market Clearing Point
MIBEL	Iberian Electricity Market
MMP	Marginal Market Price
MO	Market Operator
MW	Megawatt
NO_2	Nitrogen Dioxide
OMIE	Operador del Mercado Ibérico de Energía - Polo Español
OMIP	Operador do Mercado Ibérico de Energia - Polo Português
OPEX	Operational Expenditures
PC	Performance Curves
PT	Portugal
PV	Photovoltaic
REE	Red Eléctrica de España
REN	Redes Energéticas Nacionais
SP	Spain
UK	United Kingdom

Nomenclature

N_T	set of hours ranging the considered scheduling period
N_{UT}	set of thermal units owned to the GenCo
N_{UH}	set of hydro units owned to the GenCo
N_{UW}	set of wind units owned to the GenCo
L	set of blocks for piecewise linearisation of the hydro units performance curve
M	conversion factor equal to $3.6 \cdot 10^{-3}$ $[Hm^3 s/m^3 h]$
$d_{1_{t,k}}$, $d_{2_{t,k}}$	binary variables used for the discretisation of the performance curve of hydro units
$I_{t,i}$	binary variable equal to 1 if thermal unit i is online at time t
$I_{t,k}$	binary variable equal to 1 if hydro unit k is online at time t
$I_{t,u}$	binary variable equal to 1 if wind unit u is online at time t
$P_{t,i}$	energy produced by thermal units at time t $[MWh]$
$P_{t,k}$	energy produced by hydro units at time t $[MWh]$
$P_{t,u}$	energy produced by wind units at time t $[MWh]$
$P0_{1_k}$	minimum power output of hydro unit k for performance curve 1 $[MW]$
$P0_{2_k}$	minimum power output of hydro unit k for performance curve 2 $[MW]$
$P0_{3_k}$	minimum power output of hydro unit k for performance curve 3 $[MW]$
$V^{Sale}_{Bilateral_t}$	total energy sold through bilateral contracts at time t $[MWh]$
$V^{Purchase}_{Bilateral_t}$	total energy bought through bilateral contracts at time t $[MWh]$
$V_{Pool_{t,i}}$	energy produced by thermal units at time t sold in the pool $[MWh]$
$V_{Pool_{t,k}}$	energy produced by hydro units at time t sold in the pool $[MWh]$
$V_{Pool_{t,u}}$	energy produced by wind units at time t sold in the pool $[MWh]$
SU_i	start-up costs for thermal units i [€]
SU_k	start-up costs for hydro units k [€]
SD_i	shut-down costs for thermal unit i [€]
$u_{t,k}$	water discharge of hydro unit k at time t $[m^3/s]$
$u_{l_{t,k}}$	water discharge of block i of hydro unit k at time t $[m^3/s]$
$U^{max}_{l_k}$	maximum water discharge of block l of hydro unit k $[m^3/s]$
$U^{min}_{l_k}$	minimum water discharge of block l of hydro unit k $[m^3/s]$

$v_{t,k}$	water content of the reservoir associated to hydro unit k at time t $[Hm^3]$
V_k^{min}	minimum content of the reservoir associated to hydro unit k $[Hm^3]$
V_k^{max}	maximum content of the reservoir associated to hydro unit k $[Hm^3]$
VL_k	lower level limit of the reservoir associated to hydro unit k $[Hm^3]$
VU_k	upper level limit of the reservoir associated to hydro unit k $[Hm^3]$
$y_{t,i}$	binary variable equal to 1 if thermal unit i is start-up at the beginning of time t
$y_{t,k}$	binary variable equal to 1 if hydro unit k is start-up at the beginning of time t
$y_{t,k}$	binary variable equal to 1 if hydro unit k is start-up at the beginning of time t
$w_{l_{t,k}}$	binary variable equal to 1 if water discharged by hydro unit exceeded block l
$W_{t,k}$	hourly water inflow of the reservoir of hydro unit k at time t $[Hm^3/h]$
$z_{t,i}$	binary variable equal to 1 if thermal unit i is shut-down at the beginning of time t
π_{Pool_t}	forecasted market clearing price for the day-ahead market [€/MWh]
$\pi_{Bilateral_t}^{Sale}$	forecasted sale price of bilateral contracts at time t [€/MWh]
$\pi_{Bilateral_t}^{Purchase}$	forecasted purchase price of bilateral contracts at time t [€/MWh]
$\rho 1_{l_k}$	slope of block l of the performance curve 1 of hydro unit k $[MW/m^3/s]$
$\rho 2_{l_k}$	slope of block l of the performance curve 2 of hydro unit k $[MW/m^3/s]$
$\rho 3_{l_k}$	slope of block l of the performance curve 3 of hydro unit k $[MW/m^3/s]$
τ	time delay between consecutive hydro units $[h]$

Introduction

1.1 Contextualisation and Motivation

The electricity sector presents itself as a strategic area for both the economy and the sovereignty of states, not only by its impact on services, but also by its importance on the daily life of companies, industries and households. Therefore, it is expected that the optimisation and improvement of efficiency in the sector result in a relieving of energy costs — a powerful contributor to the financial burden of almost all activities.

Electricity is mainly produced in large power plants, away from major centres of consumption, typically in suburban and industrial areas, due to technical and economic reasons, including availability of primary energy resources as well as infrastructural and environmental constraints. The electrical energy produced in large plants is delivered to the transmission system, consisting of high voltage power lines — the energy highways. Through transformers, power flows from high to medium and low voltage distribution networks, and then to consumers, the base of the electricity value chain.

Generation units vary with respect to size, production cost, technology, fuel, and the time required to respond to orders of dispatch (i.e., the time elapsed from the moment when the decision to generate electricity is taken and the moment when it is delivered to the grid). From the point of view of both market and grid operators, units with more flexibility and dispatch-ability represent higher value. Controlling such units offers the opportunity to adapt production to instant consumption, maintaining equilibrium and ensuring the security of supply [1].

Regional geopolitics, geographical barriers and the availability of natural resources are natural shapers of the diversity and characteristics of electrical systems across the world. Given that, the recent modernisation of electricity generation fleets (and related infrastructures) into a renewables-based production towards a more sustainable power sector is often constrained by the same factors as well as by cost and technical suitability of solutions.

The global introduction of renewables for mass electricity production, which became all too apparent during the last twenty years, has embodied an attempt of countries to limit their CO_2 emissions — and meet the targets defined and signed at the last *Conference of the Parties*, embodied in the *United Nations Sustainable Development Goals* — as well as their risk exposure to fuels price oscillations, which have proven significantly unstable due to several phenomena, such as armed conflicts, cartelisation, price manipulation and economic wars. Overall, this policy has led to an increased external independence of the primary energy's importing countries, promoting greater safety of supply. However, these deep changes in the electrical systems, as they are being made, have also involved the rise of some consequent issues that might disturb the balance and operational *status quo* of the electrical sector.

Abreast renewables' deployment, investment on cleaner fossil-based technologies is a key-alternative onto a more sustainable electricity system. As fossil fuels represented 65% of the world's electricity mix in 2015, the deployment of cleaner electricity production technologies assumes a clear and logical pathway towards the decarbonisation of the sector. IEA's forecasted scenarios for climate change mitigation, released under the "Energy Technology Perspectives 2015" publication, stated that, under a 2-degrees scenario (2DS)[1], in 2050, fossil fuels will still play an important role, accounting 20% of the overall produced electricity, whereas, considering a 6DS[2], fossil fuels would remain stable and continue to lead as the main source of electric generation. However, despite the considerable importance that hydrocarbons are expected to play, even in the 2DS, only 7% of the electricity produced by fossil-fuelled thermal plants is generated by facilities without carbon capture and storage — mainly gas-fired facilities with low capacity factors, running occasionally when renewables balancing is necessary, which would allow an average CO_2 intensity of about 40 gCO_2/kWh (533 gCO_2/kWh in 2012). In order to achieve such ambitious goals, countries must start to act and pave the way with strategic plans to contain and reduce greenhouse emission gases. On the contrary, if a strong dependency on fossil fuels endures, leading to a 6DS, an average CO_2 intensity of 480 gCO_2/kWh will be the most probable scenario, a completely contrasting forecast when compared with what should be achieved to remain under the 2DS (see Figure 1.1).

[1] The 2-Degree Scenario (2DS) is the main focus of Energy Technology Perspectives. The 2DS lays out an energy system deployment pathway and an emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C. The 2DS limits the total remaining cumulative energy-related CO_2 emissions between 2015 and 2100 to 1 000 $GtCO_2$. The 2DS reduces CO_2 emissions (including emissions from fuel combustion and process and feedstock emissions in industry) by almost 60% by 2050 (compared with 2013), with carbon emissions being projected to decline after 2050 until carbon neutrality is reached [2].

[2] The 6-Degree Scenario (6DS) is largely an extension of current trends. Primary energy demand and CO_2 emissions would grow by about 60% from 2013 to 2050, with about 1700 $GtCO_2$ of cumulative emissions. In the absence of efforts to stabilise the atmospheric concentration of greenhouse gases, the average global temperature rise above pre-industrial levels is projected to reach almost 5.5°C in the long term and almost 4°C by the end of this century [2].

Figure 1.1: Evolution of regional electricity generation mixes under the 2DS [2]

One of the main aspects of the undergoing global energy transition is the variable nature of the production of new CO_2-free technologies that are currently in great expansion. Despite the fact that significant deployment of technologies — such as wind and photovoltaic — has indeed the power to reduce greenhouse gases' emissions (GHG), the uncertainty that characterises these energy sources, and hence their output, presents important and complex challenges to the grid.

The second aspect concerns the decentralised nature of low- and medium-power production facilities — small hydro, wind or solar photovoltaic — and their necessity to be often installed in remote areas where optimised production can be achieved. Consequently, both the scale and the scattered production raise significant challenges of interconnection to the grid, making them more suitable to be connected to distribution networks rather than to high-voltage lines [3].

The third aspect is related to the fugacity of market conditions: thermal-based electricity generation is very dependent on financial and commodities markets, since fuel prices are the main drivers which influence production costs. Therefore, dynamic prices of oil, gas or coal induce significant changes on the generation unit's merit order. The current panorama of fuel prices, for instance, dictated by political and international relations, reveals an implosion of coal prices over the past few years (Figure 1.2). This sharp fall is mainly caused by the *shale gas boom* occurring intensively in the United States of America, where a significant share of the internally produced and once consumed coal has now to be drained out to other regions, "flooding" the market. The effects of excess of coal in the market are being felt in the Europe, as coal prices fell and remained significantly low during the last years. At the

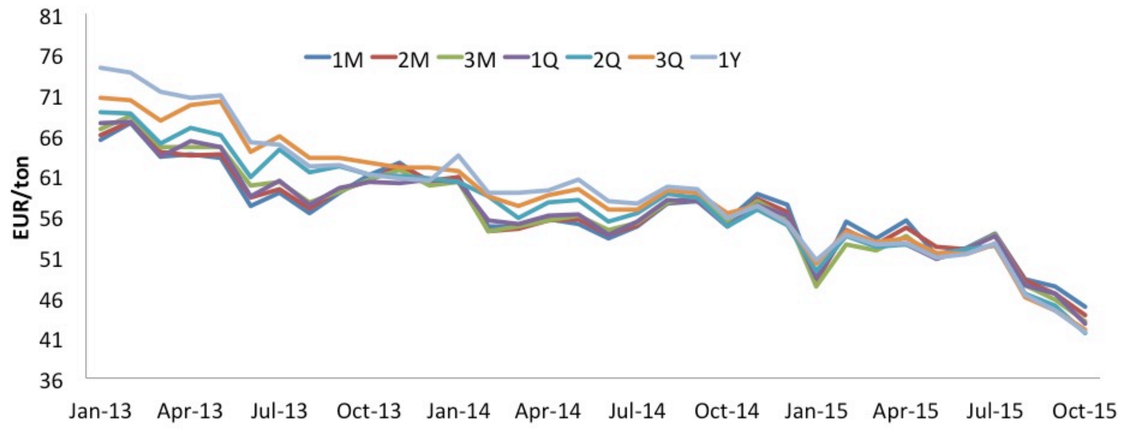

Figure 1.2: Evolution of coal prices in several maturities (Jan13 - Oct15) [5]

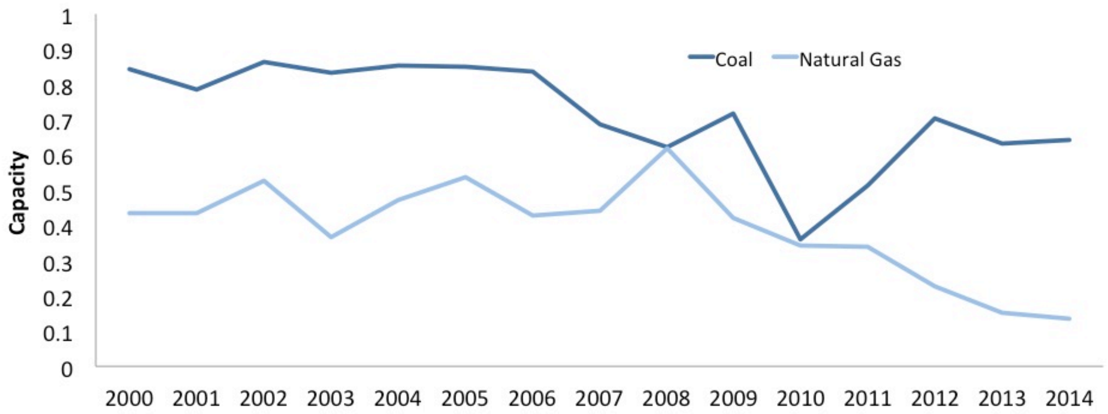

Figure 1.3: Evolution of capacity factors of gas- and coal-fired power plants in Portugal (2000-2014) [6, 7]

same time, high regional prices of natural gas and geo-political conflicts whether in Eastern Europe, Middle East or Northern Africa, have increased doubts and reticence among gas market's users, namely in the electricity production sector. Consequently, the pressure exerted by low coal prices and the absence of an efficient and strong carbon european market on other technologies, particularly gas, have yielded perverse effects on the path towards the CO_2-free electricity generation targets and the environmental sustainability of European countries [4]. In fact, capacity factors of gas-fired power plants have been decreasing over the last few years due to the growing installed capacity and decreasing generation shares. On the contrary, the coal-fired capacity has seen its capacity factors rising (Figure 1.3). This reality results in significant setbacks in terms of sustainability policies, affecting, most of all, the environment and threatening the achievement of climate change mitigation goals, by increasing electricity's CO_2 intensity.

All the mentioned conditions — price variation of primary energy sources, intermittent production of most of the newly added (renewable) installed capacity and scattered generation — are just some of the contributors which justify the development of computational systems that allow specialists to study the dynamic of markets and allow market participants to foresee and plan their actions in advance. Such tools, often called "market simulators", can be part of the necessary decision-taking process for the technical governance of utilities. Additionally, and among others, these software tools provide invaluable support to study the impact that different technologies, such as Carbon Capture and Storage (CCS), battery storage banks or pumping storage, may have on the market, being a source of knowledge on the behaviour of marginal costs, generation units' merit order and electricity market-clearing prices.

By using accurate self-scheduling models, producers are provided with invaluable help to manage their unit portfolios in order to achieve their goals — profit maximisation, costs minimisation or others. At the same time, market simulators constitute an important platform for researchers who try to adapt market rules, processes, and policies to a non-static reality. Simulations, generally developed under multi-agent systems (MAS), provide an approximation to "real" decisions, and can be important to all market participants.

1.2 Objectives

The main objectives of this thesis are as follows[3]:

1. Study the existing models for electrical energy generation, namely those who seek a proper market settlement towards the maximisation of profit;

2. Study the main energy markets, particularly the day-ahead market and the bilateral contracts market;

3. Study the multi-agent simulator "MAN-REM", which permits market participants to enrol in energy transactions, negotiate bilateral agreements [8, 9], colligate with each other [10], and manage the active role of consumers [11, 12];

4. Adopt some of the self-scheduling models referred in (1) and expand the existing version of MAN-REM by developing and implementing computational agents which simulate electrical energy producers, and whose operations are particularly based on those models;

5. Expand MAN-REM by adding market simulation functions for very-short over-the-counter bilateral contracts clearing;

[3]This work was performed under the project MAN-REM (FCOMP-01-0124-FEDER-020397), supported by both FEDER and National funds through the program "COMPETE–Programa Operacional Temático Factores de Competitividade" and "FCT–Fundação para a Ciência e a Tecnologia".

6. Develop a case study to demonstrate the functioning of the self-scheduling models added to the MAN-REM;
7. Develop a case study regarding the trading of high renewable electricity levels on the wholesale market and evaluate its impact on the day-ahead market prices;

1.3 Structure

This dissertation is divided into six chapters: *Introduction*, *Liberalised Electrical Energy Markets and Multi-Agent Systems*, *Portfolio Optimisation and Self-Scheduling Models*, *MAN-REM Extension*, *Production Scheduling - Case Studies* and *Conclusion*. In the first chapter, one can find a short introduction and contextualisation of this work as well as its main objectives and the structure of this document.

The second chapter is entirely dedicated to a concise explanation of a broad range of topics that were considered relevant to this work. Platforms for electricity trading, most common maturity periods for its transaction, principal market agents and a summary of the Iberian electricity market (MIBEL) regarding its composition, operation and challenges due to the deployment of variable clean electricity generation technologies are also addressed.

The third chapter presents a selection of three optimisation models, developed for generation companies to self-schedule their production. The models will be added to the pre-existing MAN-REM simulation software, increasing its features.

The fourth chapter presents an exhaustive description of the developments made to the MAN-REM simulator, including all the JAVA-programmed windows, which constitute the new interface, built to allow an user-friendly use of the software and its inherent markets.

The fifth chapter presents two case studies. The first is meant to demonstrate and analyse the new features of the MAN-REM simulator by testing its response to several input data, and the second to demonstrate (through a market simulation) the effect of high levels of variable renewable penetration on the day-ahead electricity pool market prices.

Finally, conclusions arising from this study and suggestions for further work developments and improvements to the MAN-REM software, regarding the simulation of electricity trading under a liberalised electricity market, are present in the sixth chapter.

Liberalised Electrical Energy Markets and Multi-Agent Market Simulators

Since the early times of the electricity sector, scale economies and transaction cost savings achieved with vertical integrations favoured the emergence and establishment of natural monopolies. This sector was therefore controlled by single public or private companies, properly regulated — since the 1980's — by state agencies [13]. In Portugal, as in many other countries, the four key-business components of the electricity sector (generation, transmission, distribution and retail) were owned by the same monopolist firm: Energias de Portugal (EDP).

Traditionally, power plants were run according to central dispatch directives which ensured the stability of the system. Regulated prices or tariffs have generally failed to signal real generation costs, aiming above all, maximising social welfare and limiting the power held by monopolists in the market, but disregarding the fundamental efficiency and sustainability of the industry and the correct remuneration of all interveners [14, 15].

The *Electricity Pool of England and Wales* appeared in 1990 as a first glance over the coming reforms that started to occur across Europe and in the United States of America. To replace the existing system, the British government designed a wholesale market, where all generation companies could sell their output on the same terms [16]. Besides the maintenance of the technical stability of the electric system, such solution also aimed the achievement of a mandatory remuneration for the produced and consumed energy. Additionally, British authorities wanted to help participants to schedule their market positions by setting conditions to get more stable prices.

In fact, this decision has effectively led to significant competition in both generation and supply sides, which was clearly demonstrated by a fall of the electricity prices to consumers of above thirty percent [16]. As a result of this reformulation, the British model for the electricity sector was followed in many other countries, and the pool platform became a symbol of the liberalised market.

In 1996, the European Commission approved the first European Directive [17] for the energy sector, embodying the will to liberalise its activities under the light of the above principles. The Directive 96/92/EC has broaden the access conditions to networks and solved the issue of determining the cost of transmission infrastructures. Standardised rules were also set for production, transmission and distribution. The spirit of competition ensured that consumers would be free to choose their electricity supplier and that new capacity should only be allocated through authorisation or be awarded by tender [18].

The challenges posed by the liberalisation of the electricity sector are usually convergent: to abolish barriers and dismantle old monopolies, design a new architecture for the sector's organisation and improve the allocation of resources to achieve an optimum, mainly comprised of financial sustainability, improved social welfare and market efficiency.

In this sector, the principle of dismantling vertically integrated activities into different and independent segments of the value chain emphasises three key-measures: decoupling activities (*unbundling*), stimulating access to the grid by third-parties, and the creation of independent regulatory authorities [18]. We should be aware that the switchover from regulated monopolies to competitive markets, in which consumers have the possibility to choose their supplier freely, does not mean only the increase of the number of operators [13]. Under this scenario, the risk for producers increases (theoretically) but, at the same time, they get greater freedom to establish their own strategies in order to maximise profits, taking into account, of course, the behaviours of their competitors [13].

During the late 90's, there was the conviction that developing a Single European Energy Market would be a no easy task, given the wide variety of existing solutions in the Member States and their variety of liberalisation degrees. Furthermore, the European geography also presents specificities that do not facilitate the interconnection of networks: it consists of a central core — France, Germany and Benelux — and peripheral regions — the UK and Ireland, Scandinavia, the Italian Peninsula and the Iberian Peninsula. Weighted these constraints, it seemed preferable to draw on the experiences of existing or arising regional markets and then, from that point, start to build the Single European Energy Market. As a consequence of such plan, the Portuguese Government proposed to the Spanish Government, in 2000, the creation of a new regional electricity market, the MIBEL [18].

2.1 Considerations on Market Competition and Regulation

Energy markets, as many others, are independently regulated. Thereby, regulators are responsible for defining prices and tariffs that rule transactions between producers, retailers and consumers. As a matter of fact, regulation entities may also act as supervisors, ensuring that all actors comply to the existing rules, and punishing them otherwise. Traditionally, state-regulated activities intent one of the following main purposes: intervention towards a more efficient market or promotion of a maximised social welfare through greater equity, solidarity between individuals and regions, as well as guaranteeing basic social needs [19].

The relationship between cost and product valuation, made by consumers, is essential to understand and evaluate the level of efficiency of a market. Hence, the pure seeking of efficiency by gradually lowering the production cost of an asset is not the only condition to achieve effective efficient market conditions. In every single liberalised activity, the value of a good or service is defined by the price consumers are willing to pay in order to adquire it. As a consequence, the true value of an asset is dictated by the price paid for the last consumed unit. This definition leads to the essence of the concept "*market efficiency*", which states that a truly efficient market is attained when consumers valuation of a good is equal to the exact cost at which the producer incurs to produce it — often known as *marginal production cost* [19].

2.1.1 Traditional Market Structures

Monopoly

For a long time, the electricity sector was ruled as a monopoly due to the idea that, despite the absence of competition, it was the most efficient operational market regime. Electricity companies were vertically integrated, from production to retail. Some of them can still be found across Europe, operating now in liberalised markets as former-monopolist companies: EDP (Portugal), Enel (Italy), or EDF (France). A classic monopoly situation is achieved when a market is composed by a single producer or a restricted group of producers acting as a cartel. Such absence of real competition among producers was often regulated by an independent agency in order to limit their market power over consumers and to guarantee access to the population.

Oligopoly

An oligopolistic market is broadly defined as a restricted number of producers who are responsible for providing a certain good or service. Due to this limited range of service/good providing companies, some of them hold significant influence on the market, which gives them the power to continuously influence prices. Consequently, competition is mainly punctuated by interaction strategies, not only with consumers, but most often with producers. This market framework has been deeply studied since the nineteenth century and often modelled by well known models such as Cournot's or Bertand's. The exercise of profit maximisation made by producers operating in oligopolist markets gets more complex than that made by monopolist companies. In fact, most of the times, the equilibrium situation for an oligopolist market often results in lower prices [3, 20].

Perfect Competition

In order to exhibit characteristics of perfect competition, a market must guarantee one major requirement: the existence of a range of both producers and consumers large enough to assure that none of the market participants hold sufficient market power to influence prices and quantities. This particular model also implies a perfect efficient market, where marginal production costs equal the price consumers are willing to pay, whereas in the long-run, marginal costs should equal minimum average production costs. Following the above premises, it is clear that a producer, in a perfectly competitive market, produces the exact quantity of a good/service socially accepted, and thus, that consumers can absorb. Additionally, if long-run convergence is achieved, producers are actually operating with minimum possible costs, avoiding unnecessary waste and use of scarce resources.

2.2 Key Market Entities

The electricity market is comprised of several key entities who ensure that households, industry and services receive a proper electricity delivery service with considerable safety and reliability:

Generation Companies (GenCos) are responsible for producing electrical energy and sell it through the variety of trading mechanisms at their disposal. They can also provide a range of ancillary services to the System Operator, helping this entitiy to maintain the electrical balance of the grid, and consequently the security of the system. GenCos can also participate in the market by buying energy to their competitors, whether for immediate delivery or to cover eventual imbalance risks. Each company can own a single power plant or a portfolio of producing units that, depending on the dimension, may provide the producer considerable power to influence the market.

Transmission Companies are responsible for the operation, maintenance and development of transmission lines, transformers and reactive compensation devices. Transmission companies often play the role of the Transmission System Operator. They are, by nature, the last stronghold of former monopolies, due to the enormous costs inherent to the construction of a transmission grid.

Distribution Companies own and are responsible for the operation of the distribution network. Due to technical and financial constraints, and even in partially liberalised systems, the distribution sector is hardly subject to competition. Such constraints are naturally related to the need of having a physical grid for each competitor, which would greatly increase costs.

Retailers are entities responsible for the resale of the electricity bought from producers in the wholesale market. Since they are non-supervisor actors who do not need to own physical infrastructures to operate, retailers have proliferated in liberalised systems. These entities buy electricity from generation companies and use — and pay a tax for — both transmission and distribution lines in order to supply small customers, ‘’located” at the end of the chain.

Consumers are commonly categorised according to their level of consumption. Small consumers include domestic consumers and small companies which means they do not possess enough power to influence the market. Consumers in liberalised markets are free to choose the retail company to whom they agree to buy electricity. On the other hand, large consumers, due to their dimension and consumption volumes, can operate in the wholesale market and buy electricity directly to generation companies. In general, large consumers represent large industrial facilities that may be directly connected to the transmission network.

The Regulator is most commonly embodied by a government agency, responsible for ensuring the efficiency and transparency of all operations that occur within the sector.

The Transmission System Operator (TSO) is an independent actor responsible for running the last resort market and balancing demand and supply in real-time towards a secure electrical system.

The Market Operator (MO) is responsible for managing both sale and purchase bids, matching them and guaranteeing the proper course of all trading processes. However, for -short and very-short horizon transactions, the Independent System Operator assumes the leading role.

2.3 Trading Mechanisms

Distinct and simultaneous forms of power trading are common in deregulated markets, ensuring a proper technical and economical operation of the electrical sector. Power producers can bid in the spot market and/or engage in derivative contracts with buyers, setting a legal contractual bond for future transactions. Generally, both methods may be adopted by power producers to maximize their profits using the available market information. Considering the features of deregulated markets, it is essential that power producers develop generation scheduling techniques and procedures that consider the technical characteristics of the power plants' portfolio, operation limits, production costs, maintenance costs and market behaviours (*e.g.*, electricity prices) to maximise their benefits [1, 21].

2.3.1 Spot Market

The spot market is defined by its immediacy, where sellers supply goods and buyers pay for them with no reversibility of deals. As this market operates on a short-term horizon, both buyers and sellers are able to adquire and offer the exact amount of goods they need or have available, respectively. Hereupon, scarcity of goods or sudden demand increase are rapidly mirrored by higher spot prices, enhancing the considerable volatility of prices and quantities. On the contrary, a rise of the ratio supply/demand will therefore lead to a fall of prices [22]. As discussed in [15], these interactions ultimately lead to an equilibrium set by prices or, in other words, meeting supply and demand results in the transacted amount of a good and its price.

Ideally, electricity spot markets should operate based on forecasts of both demand and supply, where retailers — representing medium and small consumers — and large consumers estimate their consumption for a given period in order to place their purchase bids. Likewise, producers are responsible for setting their sale offers in order to fulfil a forecasted rate of consumption, having always in mind its profit, mostly related to production costs. In fact, such deterministic approach to the market cannot be applied, particularly in electricity trading. Generation units obviously suffer form sudden failures, technical problems, maintenances or other type of events that might originate unavailabilities. The same constraints are applicable to transmission lines that connect the electricity generation level to the grid and all the downstream infrastructures. Additionally, the fast deployment of intermittent electricity production technologies with inaccurate forecasts regarding their production output exacerbates even more this problem. Consequently, and because demand is also hardly accurately predictable, the rendering of a proper balance is specially hampered by limited and expensive storage capacity of potencial energy in water reservoirs, batteries or through high-rampage generation technologies, such as CCGT systems or more modern and flexible coal-fired power plants [23].

Pool Market

The pool platform is a representative cornerstone of the liberalised electricity market philosophy. The creation of this trading mechanism envisioned the establishment of a transparent, efficient, flexible and competitive wholesale market that could provide guarantees to producers, retailers and consumers. Although pool markets are very unusually adopted as trading mechanisms in commodity markets, they are very well established in electricity systems. One of the main features of a pool platform is the absence of a negotiation process between two (or more) parties and, therefore, the transaction process occurs with absolutely no reliance on iterative attempts to reach an agreement. Despite some circunstancial differences that may be verified from one market to another, pool sessions usually follow the following procedures:

1. Generation companies submit selling bids for a certain amount of electrical energy at a certain price;

2. Similarly, large consumers and retailers submit purchase orders, specifying both quantities and prices they are willing to pay for each energy unit.

3. The market operator ranks both purchase and sale bids in order to get a purchasing-price crescent curve and a selling-price decrescent curve, respectively (see Figure 2.1).

4. The intersection point of the two curves is computed by the market operator and results in the "market clearing point" (MCP), whose coordinates represent the "market marginal price" (MMP) and the total tradable energy volume. Therefore, the market operator accepts all generators' offers which are bellow the MMP [24] and, consequently, all GenCos located on the left side of the market clearing point see their production offers accepted and are required to supply the proposed volumes of electricity. For the sake of classification, offers to the market whose price is bellow the MMP are "in merit". Producers whose offerings are on the right side of the intersection — "out of merit" — will be excluded for the respective market's spanning period.

From this point on, several versions of a pool auction may be found, depending on the specific electricity market configuration. With regard to the offered prices by each generation entity, two main variations may be encountered: in a *price-based auction*, generators can bid at any price they find appropriated, whereas in a *cost-based auction*, prices should reflect the inherent marginal costs of each particular unit. Similarly, a pool can also be differentiated

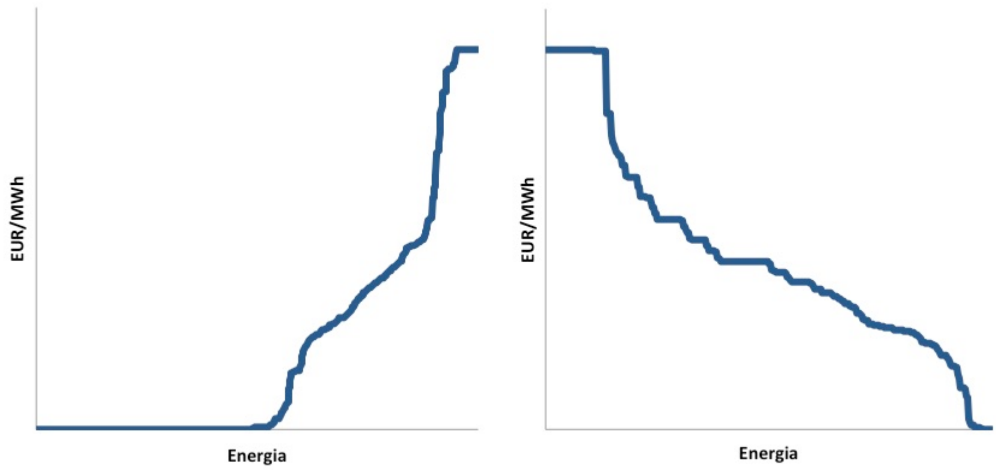

Figure 2.1: Typical supply and demand curves in a pool market session

by its initial operating assumptions and be referred to as *one-sided* or *two-sided*: in a *one-sided auction*, the demand level is predicted by the market operator, based on the theoretical concept of market inelasticity and historical records, and hence all offers from producers are cleared against this demand assumption, with no input contribution from buyers. On the contrary, in a *two-sided auction*, the market operator's dispatch is based on both buyer's demanded quantity and the supply offered by sellers.

Finally, a pool platform can also operate according to two opposed remuneration philosophies (Figure 2.2): in a *single-price auction*, "in merit" participants (buyers and sellers) pay and are paid in accordance to the resulting market marginal price, whereas in a *pay-as-bid auction*, "in merit" generators are paid the exact price they had individually submitted to the market operator.

Both trading models have strengths and weaknesses. In pay-as-bid auctions, certain behaviours are more likely to occur in order to influence the MMP (upwardly). A classic situation is observed when a generator who owns a power plant with a given marginal cost, knowing that the forecasted MMP for the next auction is significantly higher than his marginal production costs, bids at a selling price substantially above his marginal cost, having nearly the same chances of getting his offer accepted. As discussed in [15], a pay-as-bid scheme is often not adopted because it discourages generators from placing offers that reflect their marginal costs. GenCos would then try to guess the forthcoming MMP and would bid at that level of prices, attempting to maximise their revenues. Also, in a pay-as-bid situation, the absence of a single price to rule the purchase of an asset assumes a critical dimension when a price indicator is needed whether for statistical ends or as a benchmark for setting bilateral contracts [1].

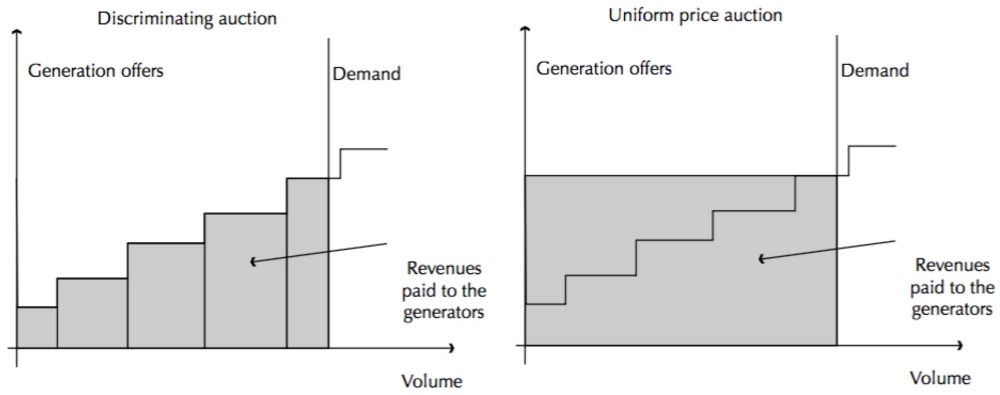

Figure 2.2: Pay-as-bid vs single-price systems in a pool market

Ancillaries Market

As already discussed, the balance of the electrical system is of capital importance. Therefore, in order to maintain the integrity of the system without compromising the electricity supply, the transmission system operator (TSO) controls a set of balancing tools, which are generally categorised according to their timescale effectiveness. Spot markets usually comprise one daily market — *day-ahead* — where participants bid their purchase and sale offers for the next twenty-four hours. A smoother maintenance of this balance is achieved, over the day, by the *intraday* market, thats aims to harmonise some natural fluctuations, allowing both producers and consumers to adjust their positions.

Although minor momentaneous imbalances do not represent a major security issue, they must be promptly detected and corrected, since frequency variations tend to weaken the system, making it much less resilient to further technical complications that may occur, harming its stability.

Such adjustments require the existence of a bench of backup units which can be “called” to perform corrective actions on production. This reserve is often subdivided into “*spinning reserve*” and “*non-spinning reserve*”. *Spinning reserve* is distinguished by its quick response, which may vary up to ten minutes, and is fundamentally oriented for frequency services — meant for constant frequency regulation. Therefore, and because of the haste these corrections require, such generation facilities are commonly equipped with a governor system which allows a direct and automated control of its power output by the ISO. On the other hand, the *non-spinning reserve* consists of production units with lower response rates — up to sixty minutes — and are specially designed to handle slower (but usually larger) fluctuations, particularly during intra-period oscillations — *the following services.*

2.3.2 Bilateral Contracts Market

Bilateral trading constitutes a mechanism for energy transactions where two parties negotiate and get an agreement without the intervention of third-parties. In transactions via bilateral contracts, almost all conditions — including price, time of delivery and energy volumes — are dependent of the goals and concession tolerance of each intervenient in the negotiation. Customised long-term bilateral contracts are flexible and negotiated privately to meet the needs of both parties. They usually involve the sale of large amounts of power over long periods of time due to large transaction costs associated with the negotiation of such contracts, making them worthwhile only when the parties want to buy or sell large amounts of energy. On the other hand, short-term bilateral contracts, celebrated within a short maturity horizon, are classified as spot market operations and usually adopt one of the following concepts:

- *Trading 'Over-the-Counter'* is a mechanism specially designed for the necessary adjustments to eventual assumed positions through long-term agreements. Producers and consumers can perform corrective actions to their previous perspectives for a given period, towards an equilibrium between demand and supply. The nature of this market makes it a low-volume energy transactions' mechanism.

- *Electronic Trading* is an electronic platform where buyers and sellers can send their offers to the market. Typically, each bid comprises four main features: order (purchase or sale), period of delivery, energy amount and energy price. When a participant sends an offer to this computerised platform, the system seeks for other submitted offers that may be matchable with it. If the matching happens to be impossible, the offer is added to a queue list, waiting for further offers that may clear it. The electronic trading is commonly used for fine-tuning of the participants positions, some minutes before the market closure.

Bilateral contracts evolved and greatly expanded over recent years. The MIBEL, as well as other electricity markets, is an example of the increasing relevance that bilateral contracts have to market participants. Besides the main goal of risk-reduction, BC present also some positive collateral effects [25], as providing greater stability in spot markets, and the curtailment of potential market power situations and reduction of demand fluctuations. Although pool markets and BC are distinct mechanisms of trading, they are naturally related and can be used to take advantage from price variations and market speculation, providing an extra source of income. Energy bought in the pool market can satisfy the bilateral deals assumed by the producer, if such prices prove to be lower than the inherent marginal costs for energy production. Similarly, if a producer holds a position benefiting from bilaterally contracted power, he might find it financially beneficial to resell part of this power in the pool, aiming at obtaining a significant profit [25].

2.3.3 Derivatives Market

The mitigation of possible harmful effects from sudden changes in market conditions has led to the appearance of derivative products, which induce more predictability and reduce risk exposure. These instruments are most commonly found as legal private transaction contracts establishing agreed quantities and negotiated prices for a certain asset. In fact, some of these contracts can be highly complex, to a point that contracted quantities and prices may vary hourly or according to existing intraday tariffs [26].

The market transactions can be physical or purely financial. On one hand, financial transactions are cash-settled, with the cashflows calculated through formulas referencing energy prices established in different markets (and possibly other prices and variables). On the other hand, physical transactions require the delivery of physical electricity, for instance spot transactions are, by definition, physical transactions. These transactions are often structured using the templates developed for the financial markets, including swaps and options [1]. Some of the most vulgar derivatives mechanisms are presented and briefly explained below:

- *Forward contracts* are one of the simplest derivative mechanisms and involve agreements on energy volumes and prices, for future transaction events, on previously scheduled delivery dates. Further details are also usually safeguarded, such as energy quality and penalties for default. Therefore, this tool allows two parties to set an agreed price of a given volume of energy, capping eventual losses which may occur in future pool market sessions, if the evolution is not favourable. For instance, if a buyer is trying to prevent the effects of an eventual price escalade, he might be willing to pay a higher amount than the current energy price in order to reduce his exposure to price variations. This difference between the expected pool price and the contracted price is often called the "*premium*", and reflects the price producers are willing to pay in order to have predictable and controlled selling prices over a given period of time. When contracts are signed, buyers assume a "long position", while sellers take on a "short position" [15, 27].

- *Options contracts* can be materialised as "*call options*" or "*put options*". A *call option* defines the allocation of a buying right of a certain asset at a certain price (*strike-price*) to its holder, whereas the owners of a *put option* detain the legal right to sell their asset according to the conditions stated on the contract [27]. Contracts can be designed considering a single-day execution date ("*European options*") or over a ranging period with a given expiration date (maturity) ("*American options*").

- *Future contracts* assume themselves, in the energy market landscape, as an opportunity for non-energy firms to take advantage from the considerable volatility of prices in energy markets. Future contracts do not carry any physical delivery of energy associated and, therefore, contribute only for market speculation. Accordingly, speculators buy and sell "paper energy", trying to profit with future price oscillations that may occur before reaching the maturity expiration date. Since some of the participants enrolled in futures are neither consumers nor producers, as the date of delivery approaches, contract holders have to balance their position in the physical market (either buying or selling).

- *Contracts for Differences (*CfD's*)* are purely financial-driven contracts, not involving any physical transaction of electrical energy, and used to mitigate the exposure to price variations. The two subscribers of a *CfD* agree upon a strike-price for the thereafter traded energy. Consequently, both parts have the legal right to be compensated by each other whenever they sell/buy energy at a lower/higher price than the agreed strike-price [28].

2.4 Effect of Renewables on the Electricity Spot Market

Currently, at a time when the penetration of renewable energy technologies is already extremely relevant in many countries (see Figure 2.3), another phenomenon arising from the mass production of "non-conventional" intermittent electricity has undergone a deep study and some discussion: the influence that non-dispatchable technologies — wind and solar in particular — have on electricity market prices [29, 30].

In pool markets, as explained in detail in Section 2.3, market operators aggregate purchase and sale offers, previously submitted by buyers and sellers, sorting them according to a meritocratic hierarchy which sets the price and amount of the electricity traded. From the time when this mechanism was primordially designed, in the early 1990's, until now, reality has being severely changing due to renewables deployment [31].

At the origin of these changes is the sorting logic of production units: based on operational expenditures (OPEX) — very dependent on the cost of fuels and susceptible to rapid changes in extraordinarily limited time periods. Thus, marginal costs of fuel-fired power plants are closely related to the price of commodities in the market, being possible to establish a link between the evolution of the plants' operating costs and the price of fuels.

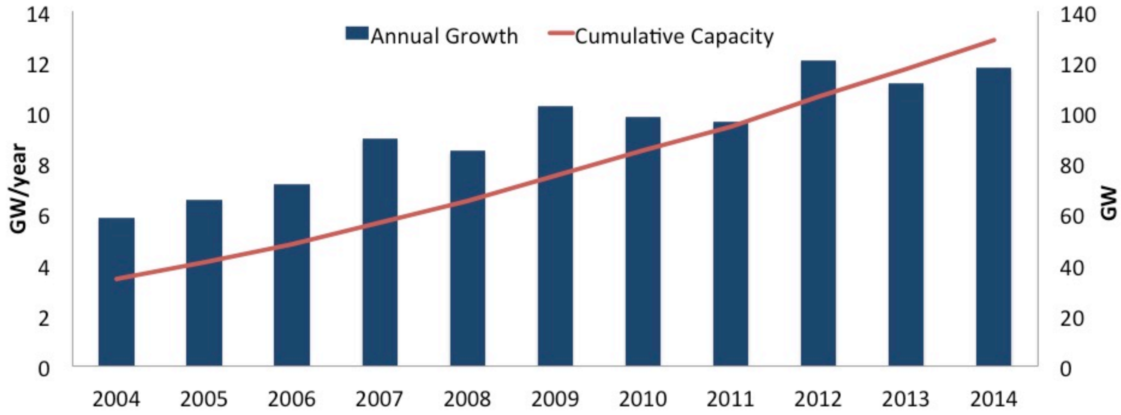

Figure 2.3: Annual wind power installation in the EU (2004-2014) [29]

Contrary, costs from photovoltaic or wind technologies are mainly influenced by capital expenditures (CAPEX), due to the large initial investments needed for construction and limited capacity factors. Given that, the OPEX of wind projects can be considered a minor cost in comparison to its CAPEX, particularly due to “free fuel” [32].

The combination of this bidding selection process with the fact that the marginal costs of wind or PV generation are considerably lower, led — over the years — to a change of the traditional shape of the supply curve. Despite frequent assumptions of null marginal costs for wind power production, it is essencial to account operation and maintenance variable costs (O&M) which include predictive maintenance — activities performed on equipments expected to fail soon, typically based on the results of condition based monitoring — and corrective maintenance — performed to repair equipments that are damaged or underperforming. Depending on the literature and also on the specific characteristics of each electric grid, estimations of marginal costs may vary considerably [33, 34], being estimated to range up to 12 €/MWh. Moreover, costs arising from the integration of this type of technology into the electricity system were also considered and comprise [35]:

- Additional system reserve costs:
  - Additional requirements for instantaneous and frequency keeping reserves;
  - Additional requirements for scheduling reserve;
- Additional system generation capacity costs;
- Transmission constraints and reinforcement costs driven by wind power.

Hence, total wind power marginal costs were estimated below 14 €/MWh.

Through the following historical data records of three "characteristic days", one can instinctively understand the referred effect of wind production in MIBEL pool prices: the $22^{th} April, 2013$ — medium wind production (P_{av} = 1 483 MW) —, the $8^{th} December, 2013$ — low wind production (P_{av} = 64 MW) — and the $4^{th} January, 2014$ — high wind production (P_{av} = 2 950 MW).

Figure 2.4 illustrates a medium wind production day with an average hourly output of 1 483 MW, whereas Figure 2.5 illustrates a low wind-based electricity generation characteristic day with an average hourly output of sixty-four megawatt, and Figure 2.6 depicts a high wind production day with an average output of 2 950 MW — corresponding to capacity factors of about 1.3%, 32.0% and 65.0% of the Portuguese installed capacity, respectively [7].

By analysing Figures 2.4, 2.5 and 2.6, it turns easier to understand the subjacent effect of high wind production — whose marginal costs are below of any other traditional technology. High wind production, here represented by Figure 2.6, causes a shift of the traditional capacity to the right-side of the MCP (assuming an electricity market where demand is approximately inelastic). Examining the changes induced by the introduction of wind production, a major effect is easily distinguishable: a decline of the marginal market price. This effect is often known as "merit of order effect" [36].

By comparing both annual maximum and minimum wind generation days, the correlation between wind production and pool prices is even more evident: while on the 8^{th} December, with very low wind production output, hourly prices in MIBEL ranged from 83.4 €/MWh to 111.0 €/MWh, on the 4^{th} January, the high production output from wind farms led to extremely low pool prices in the Iberian market, ranging from 0.0 €/MWh to 19.0 €/MWh. An intermediate case, represented by the case of 22^{th} of April, shows an average production situation where the outcoming prices were around 25.0 €/MWh.

Through this example (not necessarily simplistic), it can be concluded that wind power contributes for considerable energy cost savings. Therefore, it follows that a substantial presence of wind technologies in the market may lead to increased overall efficiency of the pool mechanism, resulting in a significantly lower MMP [36, 37].

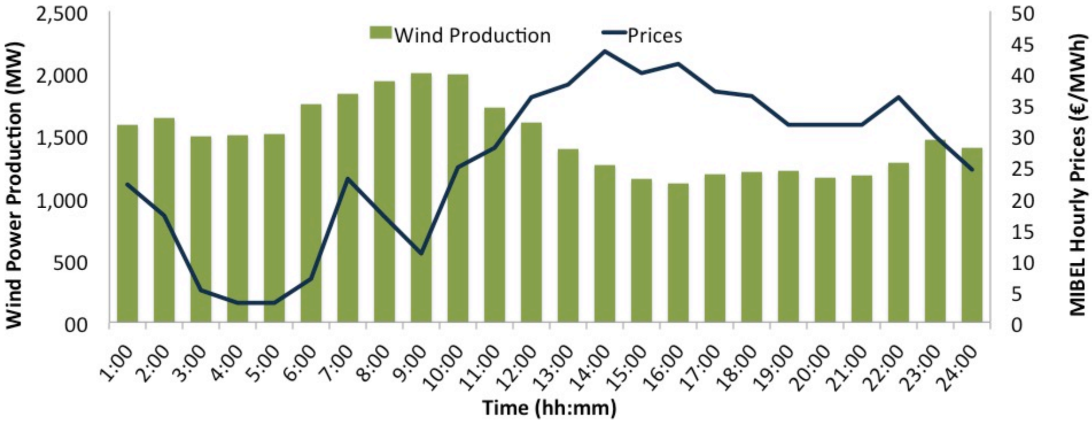

Figure 2.4: Medium wind production scenario ($22^{th} April, 2013$) [7, 38, 39]

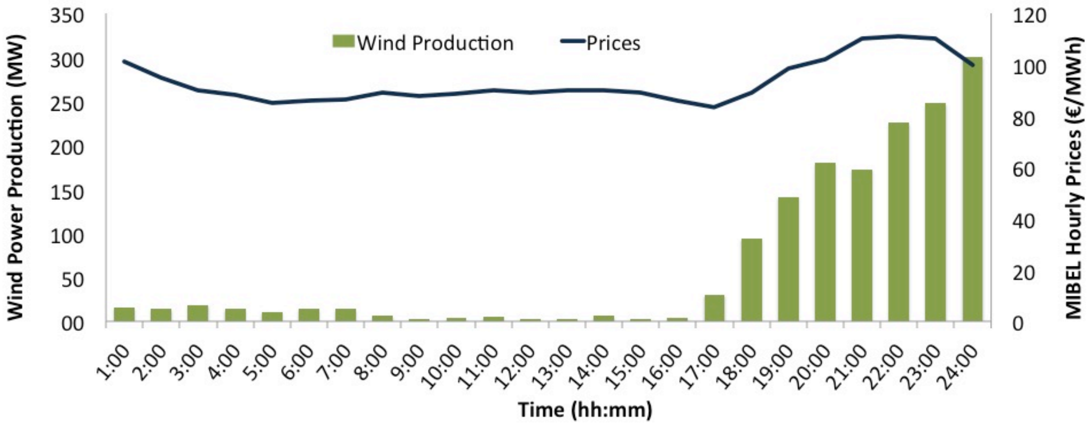

Figure 2.5: Low wind production scenario ($8^{th} December, 2013$) [7, 38, 39]

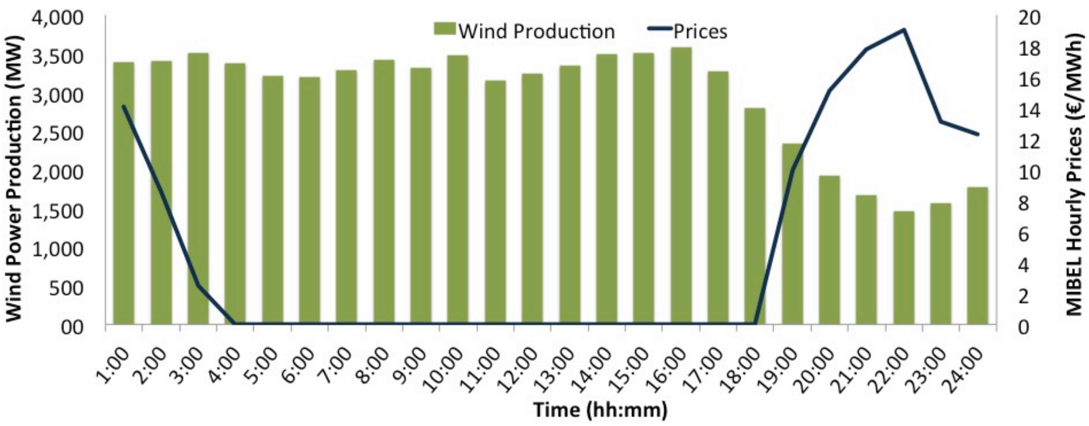

Figure 2.6: High wind production scenario ($4^{th} January, 2014$) [7, 38, 39]

However, despite going beyond the scope of this work, it should be emphasised that this economy — due to lower pool prices — may not be a net gain for consumers and, hence, it should be holistically analysed. Some studies were carried out on this matter with the intention of finding out whether there is a net benefit from the socio-economical optimisation perspective arising from high penetration of wind power, being many of them contradictory. In a study, *Azofra et al.* [40] essentially focus on the Spanish electricity generation system, and conclude that, despite the *feed-in tariffs* guaranteed to renewable energy producers — indirectly supported by consumers — the significant reduction of the market marginal price results in significant savings for consumers.

On the other hand, *Mulder et al.* [41] focused on the Dutch electricity market and concluded that the reduction of the electricity retail price is not necessarily an evidence, since a clear gain for the consumers cannot be admitted. However, this study admits the possibility that the low preponderance of renewable technologies in the Dutch electrical production system might be the cause of such ineffectiveness.

2.5 The Iberian Electricity Market (MIBEL)

The Iberian Electricity Market (MIBEL) results from the cooperation of the Portuguese and Spanish Governments, aiming to promote a better integration of both countries' electrical systems. Its significant contribution for the establishment of an integrated electricity market, not only at the Iberian level but, also at the European scale, is an important step to take on the pathway towards the envisioned "energy union" [42].

This market was fully launched on 1^{st} July 2007 and is subdivided into two main poles: the OMIE — from the Spanish side — and the OMIP — from the Portuguese side. Despite the fact that MIBEL is an unified electricity market, the OMIE takes responsibility for the spot market clearance, whereas the OMIP ensures the management of the bilateral agreements, including forwards, futures and options.

The joint regulation of the Iberian electricity market is operated by "*ERSE - Entidade Reguladora dos Serviços Energéticos*" and "*CMVM - Comissão do Mercado de Valores Mobiliários*", in Portugal, and by "*CNE - Comisión Nacional de Energía*" and "*CNMV - Comisión Nacional del Mercado de Valores*" in Spain.

Regarding the transmission industry, the Iberian market is composed by two major companies, the "*REN - Rede Eléctrica Nacional*" and the "*REE - Red Eléctrica de Espanã*", which are also responsible for the market operation. Distribution is, in Portugal, guaranteed by the monopolist company "*EDP - Energias de Portugal*" whereas in Spain, regional monopolist companies such as Union Fenosa, Endesa, Iberdrola and HC Energia are the providers of this service.

2.5.1 Market Organisation

Currently, the OMIE manages day-ahead and intraday transactions as well as real-time transactions for Portugal and Spain. As this is a joint market, bids from both Portuguese and Spanish sellers and buyers are aggregated and cleared in single auctions. This method often leads to uniform electricity pricing on both sides. However, despite the fact that all offers to the market are handled disregarding their origin, it is still not unusual to witness disparities among Portuguese and Spanish spot prices. Price decoupling and its consequent price spread is mostly caused by the exhaustion of the transmission capacity between territories, leading to nodal regional prices (see Figure 2.8).

The day-ahead and intraday markets represent the two main mechanisms for energy transaction in the spot market, organised by the OMIE. The day-ahead regime allows both buyers and sellers to trade energy according to their perspectives of demand loads and renewables production forecasts. Procedures for a regular pool market auction start with a twelve-hour advance from the beginning of the next day, meaning that supply- and demand-side agents must communicate their market actions to the market operator until 12:00h of the previous day (d-1)

Producers and retailers place their selling and buying bids, which are then arranged ac-

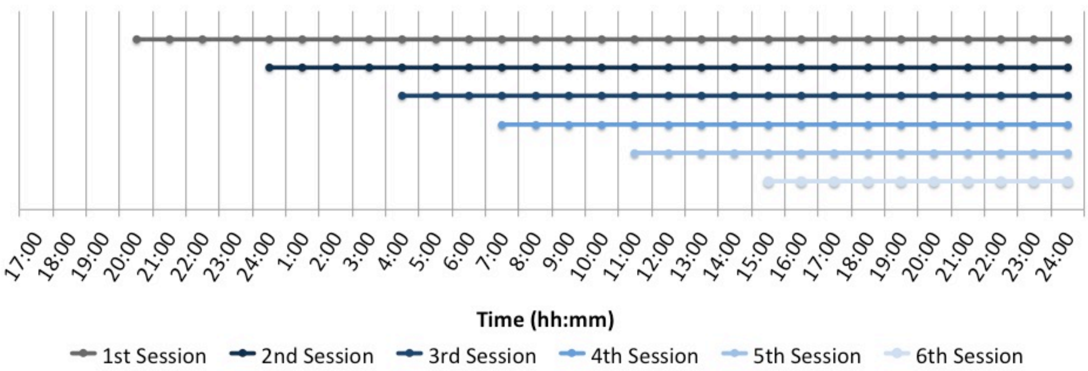

Figure 2.7: Day-ahead and intra-day market sessions [42]

cording to the proposed prices and used to draw the demand and supply curves [1, 24, 43]. However, due to natural oscillations either on the demand and supply sides or to unforeseen technical constraints, additional trading platforms with much shorter maturities provide essential adjustment services, smoothing the effects of sudden events.

The intraday adjustment tool is provided by the market operator and comprises six daily sessions where buyers and sellers can adjust their positions to the real course of both demand and supply (Figure 2.7):

- 1^{st} Session — closes at 20.00h of day $d-1$ and clears the market for the remaining four hours of day $d-1$ and for the next 24 hours of day d;
- 2^{nd} Session — closes at 00.00h of day d and clears the next 24 hours of day d;
- 3^{rd} Session — closes at 5.00h of day d and clears the market for the next 20 hours of day d;
- 4^{th} Session — closes at 8.00h of day d and clears the market for the next 17 hours of day d;
- 5^{th} Session — closes at 12.00h of day d and clears the market for the next 13 hours of day d;
- 6^{th} Session — closes at 16.00h of day d and clears the market for the next 9 hours of day d.

In addition to the spot market platforms for electricity trading made available by the Spanish pole of the MIBEL (OMIE), the *Iberian Energy Derivatives Exchange*, through the OMIP, provides a large set of derivative products such as futures, swaps, forwards and options. A wide number of contractual products with different specificities allows traders to negotiate in maturity periods ranging from days, weeks, months, up to quadrenniums. Characteristics of such contractual bonds, physical and financial, are extensively described stating, for example, whether a contract concerns base-load or peak period energy, tick volumes or the method of cash payments [44].

2.5.2 Market Main Indicators

The Iberian Peninsula and, therefore, the MIBEL, are fairly well equipped with intraconnections linking Portugal and Spain. However, they are still quite regionally isolated and far from the interconnection ratios commonly found across central and northern Europe: interconnections with Morocco and France amount 2.4% of the overall MIBEL's generation capacity, constraining exchange operations with neighbouring markets and making it impossible to export wind power generation surplus. Because a proper market union can only be fully achieved under a scenario of comfortable net interconnection capacity to accommodate transactions defined by the market, intra- and interconnection developments have been one of the main consensuses among national authorities and the European Commission. In fact, improved MIBEL's intraconnections — connecting Portugal and Spain — have decreased the effect of price decoupling (Figure 2.8) and increased the price-coupling between these two countries, reducing significantly the number of hours when locational prices were registered. Accordingly, 97.6% of price-coupling in the day-ahead market was registered in 2015.

The Iberian generation system is naturally composed by the sum of the installed capacity in the two Iberian countries. By the end of 2014, this overall capacity rounded 125 595 MW, with a contribution of 19 125 MW from the Portuguese side and 106 470 MW from the Spanish side [7].

Despite the recent deployment of CO_2-free electricity generation technologies, combustible fuels still play an important role in MIBEL, with a capacity share of 46.1% (2014), significantly comprised by coal and natural gas facilities. A closer look at the evolution of generation capacities unveils a consistent growth of natural gas. Coal and gas usage is highly variable in the Iberian countries due to their direct dependence on renewable production to meet demand and, therefore, on wet and/or windy years.

Improvements on hydro capacity were a must regarding the safety of the grid's management and balance. Pumping capacity in the Iberian countries represented 13.9% of the peak demand and 23.6% of the overall wind capacity in 2014 [7]. Portugal's pumping capacity has registered a growth of 57.0%, representing 24.8% of the overall hydro capacity in 2014. According to [45], the Portuguese authorities plan to add 1 837 MW of new hydro capacity by 2017 — including 1 295 MW of reversible capacity — and an additional capacity of 1 100 MW (reversible) by 2022.

Wind generation is high in Portugal and Spain due to the optimal resource conditions: MIBEL's wind capacity was significantly deployed, growing 213.8%, from 8 870 MW in 2004 to 27 831 MW in 2014, and accounting for 21.9% of the overall capacity and 59.9% of the peak demand capacity (2014).

Portugal and Spain have considerably suffered with the outbreak of the European financial crisis in the late 2008 — and subsequent economic cool down and shrinkage — and have registered a significant fall on electricity demand since then (8.1%). This situation, enhanced by a decoupling of some level between the economic growth and the energy consumption, has increased even more the representativity of variable generation, meaning solar and wind

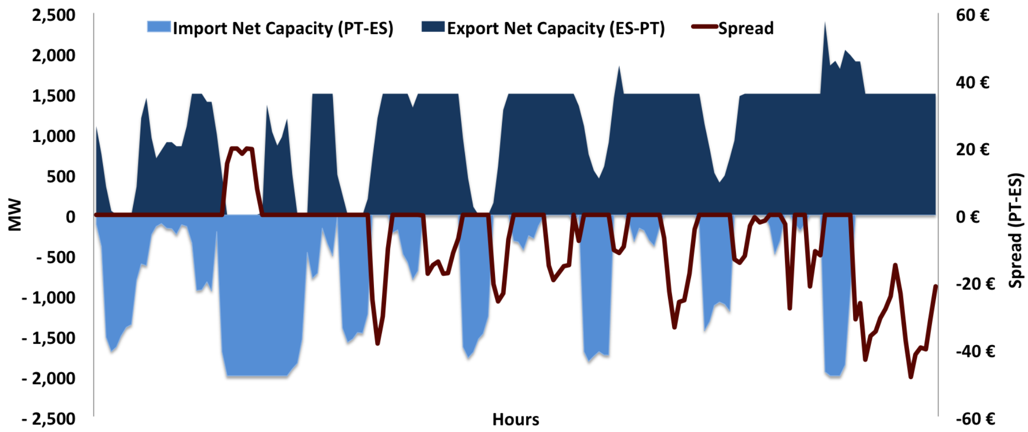

Figure 2.8: Implications of interconnection capacity on MIBEL's price coupling (19Jan2013 - 25Jan2013) [5]

power production shares (4.3% and 19.5% in 2014).

Renewables, particularly wind and solar power, have been specially deployed in European countries. In 2014, Portugal (25.4%) and Spain (21.6%) were the World's leaders on wind penetration, right after Denmark. Production variability is managed by relying on hydro pumping and gas-fired capacity to constantly balance the production.

Also in 2014, the electricity generated in Portugal from wind reached 22.9% and was the second largest contributor for electricity supply after hydropower. On its turn, Spain's electricity generation registered a 18,8% contribution from wind, making it the third main source of generation after hydro and nuclear power. On the other hand, solar capacity for electricity production has registered a 113.8% growth, reaching 7 502 MW in 2014. However, only 5.5% of this capacity is located in Portugal. In 2014, solar power contributed with 4.3% of the generated electricity in the MIBEL region [6].

Despite the fact that the pool day-ahead market is the trading mechanism by excellence in a liberalised market, the great majority of energy transactions in both countries through the MIBEL were traded via derivatives market. This situation is highly comprehensible since no producer nor consumer wants to be at the mercy of pool price fluctuations and, consequently, setting bilateral agreements with other parties, with controllable strike-prices, reduces operation risks [5].

At the same time, we have been assisting to a downward trend on MIBEL's daily average prices, as well as to the convergence between Portuguese and Spanish prices — which has only been possible because of the reinforced net capacity between both countries [39].

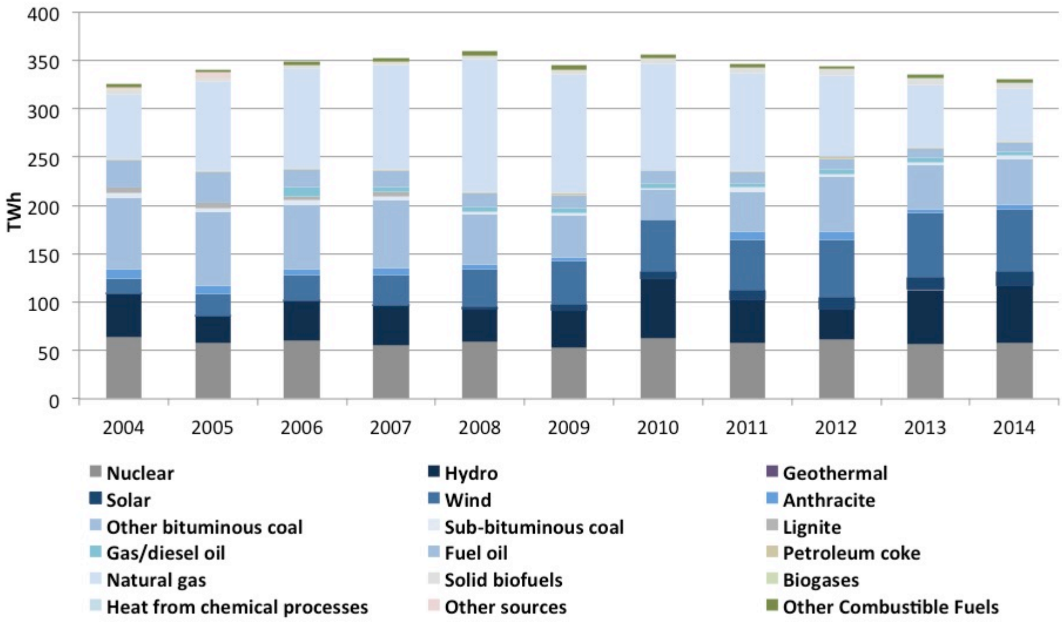

Figure 2.9: Electricity generation in Portugal and Spain, by source (2004-2014) [6]

2.6 Agents and Multi-Agent Systems

Agent-based modelling and simulation (ABMS) is a relatively new approach of modelling complex systems composed of interacting, autonomous agents. Agent-based systems may contain two or more agents, constituting multi-agent systems. Moreover, a typical agent-based system stands on three main pillars: agents, interactions and the environment.

An agent is defined by its capacity to act autonomously, meaning it can act on its own, responding to the environment, without the intervention of humans or other agents. Autonomous agents are *responsive*, meaning that they should perceive their environment and consequently respond to changes that may occur in it. They can also be *pro-active*, since their goal-seeking nature doesn't allow them to assume a simply reactive posture, being able to exhibit opportunistic behaviour and take the initiative. Generally speaking, agents are individuals that interact with their peers and even with humans, in order to complete their own problem solving [46].

Despite the above, some agents may be created with only a reactive purpose, which means that such individuals interact by making no use of historical or learning processes, responding exclusively to impulses from the environment [47].

Agents interact according to their portfolio of pre-designed possible actions, which may influence their environment (Figure 2.10). However, those actions may be subject to preliminary conditions, which ensure that the agents can effectively proceed in specific ways. Hence, the actions of an agent are often associated with pre-conditions which define the possible situation where they can be applied [47]. The mutual interaction among agents characterises social systems, where individuals are influenced and learn the other's actions, and adapt their behaviours to be more harmonised with the environment. Interactions between agents can range in a variety of natures [46]:

- Cooperation — agents assume a partnership that can take them to their common aim;
- Coordination — agents organise a problem solving activity in order to avoid harmful interactions and to exploit beneficial ones;
- Negotiation — agents define a set of conditions that must be agreed by all in order to come to an agreement.

Negotiation is a bulk issue when it takes to agents interactions. When in a negotiation situation, agents must be designed to be able to solve differences and conflicts through negotiation towards a good coordination of their activities. In multi-agent systems, negotiation requires that agents participate in a hole of chained actions which might permit a conflict resolution. Agents, therefore, prepare and plan their negotiation interactions. Secondly, they should generate, evaluate and exchange offers with its pairs and then, if possible, come to an agreement with the involved parties. The demand for an agreement between parties leads to the development of negotiation strategies which are supposed to lead to a beneficial agreement that can be as closer as possible of the agent's initial goals. According to [48], those behaviours can be mainly categorised as *Concession Making* and *Problem Solving*.

The first is a characteristic behaviour of an agent who possesses a given concession factor, which defines its willingness to sacrifice part of its initial goals, reducing its aspirations, towards a consensus among the intervenient parties. On the other hand, the second behaviour is typical of an agent who assumes a more interesting posture regarding its primordial aims, maintaining its goals and aspirations and confining itself to conciliate them with others' aspirations.

Agent-based modelling is widely used in a large variety of areas, ranging from stock markets and supply chains, to predicting the spread of epidemics and the threat of bio-warfare, via understanding the fall of ancient civilisations to modelling engagement of forces on battlefields or at sea [49]. Pedestrian crowd movements, transportation infrastructures, financial

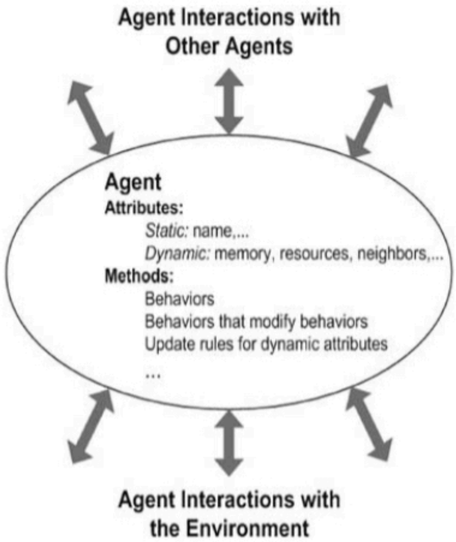

Figure 2.10: Typical agent [50]

markets, cell behaviours, population dynamics and even markets that do not exist yet, are also commonly studied and tested through agent-based systems. Such models can be developed using specific software toolkits (*e.g.* JADE). General programming languages, such as Python, JAVA and C++, can also be used with the advantage of providing specific capabilities for modelling agents [50].

2.6.1 Multi-Agent Simulators for Energy Markets

This subsection introduces some of the existing multi-agent simulators namely, EMCAS, SEPIA, MASCEM and AMES.

EMCAS

The *Electricity Market Complex Adaptive System* (EMCAS) simulator was developed by researchers from the Argonne National Laboratory (US Department of Energy) with the aim to study the evolution of the electrical system, consequences of competition on the variation of market prices as well as to assess operational limits and security criteria of the grid [51].

The EMCAS allows one to simulate the behaviour of agents enrolled in several types of electricity markets, such as the pool market and the bilateral contracts market, and constrains their activities according to eventual operational limitations of the system. Producers, consumers, distributers, market operators, the independent system operator and transmission entities are all represented by agents who are able to adapt their behaviour in order to achieve success or avoid prior failures as well as to make decisions, learn and adapt their strategies (*e.g.* biding strategies) to the environment based on historical records [52, 53]. In fact, this simulator is widely used by real-world companies across the globe, being used, for instance, by REN - Rede Eléctrica Nacional, to study and analyse the MIBEL.

SEPIA

SEPIA, standing for *Simulator for the Electric Power Industry Agents*, is a tool designed by Honeywell Technology Center and the University of Minnesota specifically oriented to bilateral contracts for trading electricity. Similarly to others, this an agent-based tool that aims to analyse the behaviours of all participants in the electricity market. SEPIA requires power specifications (generation and load), determines the operational limitations of the system and foresees eventual discrepancies on the security criteria that have been defined. Agents aim to model physical entities such as producers, consumers and system operators. Consumer agents define and provide their load profiles, stating the amount of electrical energy they are willing to buy, and interact with generation agents in order to define the contractual terms and conditions for the trade, such as price and quantity. Once both parties agree upon a specific contract, their decision is sent to the system operator, who is responsible for checking whether this transaction can be physically accomplished within the boundaries considered acceptable to run the electric grid safely [51].

MASCEM

Developed by the *Grupo de Investigação em Engenharia do Conhecimento e Apoio à Decisão* (GECAD) of the Instituto Superior de Engenharia do Porto (ISEP), the MASCEM simulator is a JAVA-based multi-agent simulator. Being a software to support decision-making, the MASCEM allows users to evaluate agents' decisions, on different markets, particularly on pool market and bilateral contracts. Agents' modelling of producers, consumers, retailers, market operators, system operators and facilitators (whose function is to coordinate and supervise simulations) is based on artificial intelligence [54].

Simulations may occur according to different bidding strategies such as time-wise dynamic strategies, strategies dependent on other agents' behaviours, historical market records and historical agents' decisions records [55].

AMES

The *Agent-based Modelling of Electricity Systems* (AMES) was designed, by the University of Iowa, USA, after the *US Federal Energy Regulatory Commission*'s (FERC) suggestion for the restructuring of the wholesale electricity market in 2013 [56]. AMES is an open-source software developed under the JAVA programming language where agents, particularly producers, possess learning skills. This simulator runs the wholesale electricity market for a predefined period of time with a minimum scale of one hour which allows to reduce forecast errors induced by the volatility of prices inherent to an electricity market. The software comprises generation agents (GenCos), retail agents (LSEs) and the system operator.

GenCos are assumed profit-seekers and exclusive sellers, which means that, unlike in the real world, electricity producers cannot buy electrical energy in the market. Learning capacities and generation technologies are an input to this simulator — allowing to determine production costs that are sent to the system operator whenever a GenCo bids in the market. Such marginal costs can be presented in the form of a costs curve above the real costs of the producer, a behaviour that is typically observed when generators want to reduce risk exposure and maximise profits. Declaring a generation capacity below their real one is also a mechanism used by GenCos to lead to higher market prices [57].

The *Load-serving entities* (LSEs), or in other words the retailers are, unlike GenCos, unable to learn. They aim to satisfy their demand for electrical energy by sending buying offers to the system operator with respect to the twenty-four hours of the next day.

The system operator (OS) is responsible for managing the wholesale energy market, seeking, above everything else, to maximise the global gain of the system, which is defined as *Total Net Surplus* in the AMES software. After receiving the GenCos' and LSEs' offers for the next day (D+1), the OS determines the prices of each of the twenty-four intervals.

Portfolio Optimisation and Self-Scheduling Models

The following suggested deterministic models describe three different ways of computing optimised selling settlements of GenCo's production depending on the nature of their portfolios. Since all considered methods maximise the overall profit over a given period, they require similar input data:

- Technical specifications of all units owned by a producer, in order to properly schedule production within the technical limits of each power plant and considering specific costs of each particular running decision;
- Day-ahead pool prices' forecast for the considered period;
- Purchase and sale prices forecast for bilateral contracts;
- Forecasted data for hydro and wind power generation units comprised of hourly water inflows in hydro reservoirs and the hourly wind production, respectively, in order to better estimate an eventual production and its selling settlement.

The considered energy market's framework is comprised of two general platforms where GenCos can participate and try to achieve the best profit possible by trading their produced energy. Specifically, producers are free to sell their production output in the pool and/or through bilateral agreements with retailers and large consumers. As a matter of fact, a producer can even buy electrical energy bilaterally and, by doing so, take advantage of an eventual rise in pool prices, by trying to resell the energy bought bilaterally in the pool, with potential net financial gain.

In real energy markets, GenCos may need to buy energy to competitors — whether in a pool or through bilateral contracts — in order to cap its risk exposure to external unexpected events, or even to guarantee the supply of a percentage of contractual obligations arising from long-term contracts. Despite the adherence to reality of such scenarios, neither long-term

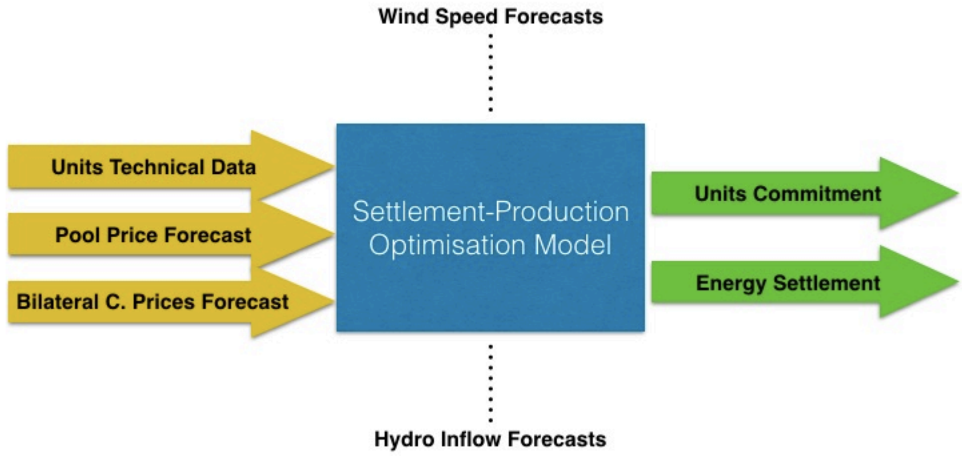

Figure 3.1: Input and output data of the considered scheduling models

contracts nor risk management are considered in the following models.

The output data made available by the models is transversal to all of them. Hence, by computing the scheduling of a portfolio, GenCos will have at their disposal the best scenarios for production settlement, meaning the proposed energy volume to be sold in the pool and the second and third lots of energy that are proposed to be sold and bought through bilateral contracts. A commitment status of each individual unit is also determined as well as their hourly production output (see Figure 3.1).

Depending on the chosen scheduling model, more technical specification details may, or may not, be used to optimise more accurately the production and its settlement towards the best profit. Hereupon, further details on individual approaches to the described problem will be discussed below.

3.1 Thermal Portfolio Model

Although clean electricity production technologies have been the recent focus of the great majority of countries, thermal generation units still play an important role in the electricity sector. Particularly, coal-fired — but also gas- and oil-fired — power plants have always been considered base-load units, due to their higher operational inertia, which did not allow big generation fluctuations, due to high start-up and shut-down costs, slow output power rampages, considerably high minimum production levels and high fixed costs. However, despite the so called "green policies", it is common thinking that fossil fuels, and thus thermal power plants, still have a crucial importance to play in the medium-and long-term future, as balancing agents of the electric system, and as the market continues to be flooded with variable renewable production. Hence, further technological research has to continue to provide this generation systems with higher flexibility and, naturally, lower costs, when operating as backup units.

The following model suggests one way of determining an optimised market settlement of electrical energy, for a generation company, on both bilateral and pool markets, towards the best possible revenue, from a given production portfolio composed by a set of thermal fossil-fuelled power plants. Such method is based on the deterministic approach formulated by *Conejo et al.* [58].

Based on an input of forecasted market prices — for both pool and bilateral markets — and on technical specifications of each generation unit, the model computes the best production scheduling for a given portfolio, including the best commitment for each unit and its hourly electricity production output. Additionally, an optimisation for market settlement is computed, providing the GenCo with the best bidding scenario towards a maximised profit. The objective function (3.1) reflects the sum of the revenues for a given period of time, minus the sum of all costs for the same period:

$$\begin{aligned} z = & \sum_{t=1}^{N_T} \sum_{i=1}^{N_{UT}} \pi_{Pool_t} \times V_{Pool_{t,i}} + \sum_{t=1}^{N_T} V_{Bilateral_t}^{Sale} \times \pi_{Bilateral_t}^{Sale} - \\ & \sum_{t=1}^{N_T} V_{Bilateral_t}^{Purchase} \times \pi_{Bilateral_t}^{Purchase} - \sum_{t=1}^{N_T} \sum_{i=1}^{N_{UT}} \lambda_i^P \times P_{t,i} \end{aligned} \tag{3.1}$$

The profit optimisation function is obtained by summing the revenues arising from both selling a variable quantity (V_{Pool}) of electricity in the pool and selling a variable volume $V_{Bilateral}^{Sale}$ via bilateral contracts. Additionally, all costs derived from electricity production (λ^P) and eventual bilateral acquisitions ($V_{Bilateral}^{Purchase}$) must be deducted. Constraints (3.2) to (3.8) ensure several technical limits as well as the logic dimension of all variables, and consequently the proper operation of the model and consistency of its output results.

$$\sum_{i=1}^{N_{UT}} V_{Pool_{t,i}} + V_{Bilateral_t}^{Sale} - V_{Bilateral_t}^{Purchase} = \sum_{i=1}^{N_{UT}} P_{t,i}, \forall t \tag{3.2}$$

$$P_{t,i} \leq P_{Max_i}, \forall t, \forall i \tag{3.3}$$

$$P_{t,i} \geq P_{Min_i}, \forall t, \forall i \tag{3.4}$$

$$V_{Pool_{t,i}} \geq 0, \forall t, \forall i \tag{3.5}$$

$$V_{Pool_{t,i}} \leq P_{t,i}, \forall t, \forall i \tag{3.6}$$

$$V^{Sale}_{Bilateral_t}, V^{Purchase}_{Bilateral_t} \leq \sum_{i=1}^{N_{UT}} P_{Max_i}, \forall t, \forall i \tag{3.7}$$

$$V^{Sale}_{Bilateral_t}, V^{Purchase}_{Bilateral_t} \geq 0, \forall t, \forall i \tag{3.8}$$

Constraints (3.3) and (3.4) state that the power output limits of each individual thermal unit should be bounded by its minimum and maximum technical output. Constraints (3.5) and (3.6) define volume limits for the energy produced by unit i during hour t sold in the pool market. Volumes of energy bought and sold through bilateral contracts are delimited by equations (3.7) and (3.8). Therefore, $V^{Sale}_{Bilateral}$ and $V^{Purchase}_{Bilateral}$ must be, individually, less than or equal to overall name-plated power owned by the GenCo. This imposed limit aims a better distribution of the power settlement on both bilateral and pool markets.

Contrary to pool prices, sale and purchase prices for bilaterally agreed contracts do not vary on an hourly basis, but according to settled contract periods. Likewise, contracted volumes assume the same value along this tariff, meaning that contracted power volumes should be respected by both buyers and sellers until the the contracted period is expired — a time when the two parties can negotiate and enrol in newly-agreed volumes for the next tariff period span.

The model also considers a mechanism to replicate the high volatility and low liquidity that characterises bilateral markets [58]. The accumulation of purchase or sale energy blocks is then discouraged by gradually less favourable prices. As the producer accumulates buying or selling blocks, his profit margin decays due to the decrease of the profitability of both selling and buying blocks.

3.2 Thermal and Wind Portfolio Model

Coordination between electricity generation technologies is more and more a key issue to secure a reliable electrical grid. Massive wind power production, that has become a reality worldwide, still lacks some reliability, and thus thermal power plants need to assist the system with backup services, balancing the grid whenever necessary. Costs of this cooperation must be taken into consideration since the greater share of thermal power capacity is still quite resilient to variability, having been built to provide a continuous and stable output production. Hence, when used to operate under a different generation regime, a careful management of his portfolio should be done by every generation company in order to safeguard eventual risks and financial losses arising from a deficient planning and/or operation of an infrastructure.

The following model suggests a scheduling optimisation method in order to maximise profits of portfolios comprised of thermal and wind generation technologies. Similarly to Section 3.1 and to the next Section 3.3, this section considers a deterministic scheduling settlement-oriented model, which aims to provide the best bidding solution in both bilateral and pool markets, and at the same time, adjusting production scheduling. Furthermore, this computacional design is based on the *Combined Unit Commitment and Emission (CUCE)* problem [59].

By considering such a hybrid portfolio, this model can be an invaluable tool, since it permits to schedule the production of each producing unit, individually, while minimising the greenhouse gases (GHG) emission and, therefore, avoiding to the maximum the inherent taxes paid as a compensation for the release of those gases. Additionally, as it considers GHG emission costs, this model can be seen as a key-tool to access the competitiveness of thermal power plants equipped with carbon capture and storage (CCS) systems, which at the cost of increasing generation costs, reduce massively CO_2 emissions.

$$
\begin{aligned}
z = &\sum_{t=1}^{N_T} \left[\sum_{i=1}^{N_{UT}} \pi_{Pool_t} \times V_{Pool_{t,i}} + \sum_{u=1}^{N_{UW}} \pi_{Pool_t} \times V_{Pool_{t,u}} \right] + \sum_{t=1}^{N_T} V_{Bilateral_t}^{Sale} \times \pi_{Bilateral_t}^{Sale} - \\
&\sum_{t=1}^{N_T} V_{Bilateral_t}^{Purchase} \times \pi_{Bilateral_t}^{Purchase} - \sum_{t=1}^{N_T} \left[\sum_{i=1}^{N_{UT}} (C_{t,i}^{p} + C_{t,i}^{e} + C_{t,i}^{su|sd}) + \sum_{u=1}^{N_{UW}} C_{t,u}^{w} \right]
\end{aligned}
\tag{3.9}
$$

The objective function of this optimisation is driven by the maximisation of the profit — the net value between revenues arising from the simultaneous energy sale through bilateral agreements and pool market, minus the costs.

Contrary to what is considered in the previous models, the cost calculation for a given GenCo is hereby much more scrutinised and close to real charges faced by any generation company. Hence, besides the obvious marginal cost of each energy unit — almost exclusively derived from fuel consumption — this method is comprised of a fixed value paid for each online generation unit, independently of its current production.

Apart from that, considering only thermal units, the model also takes into account start-up and shut-down costs, as well as GHG emissions taxes. This factor is obviously restricted to thermal infrastructures, since wind turbines do not make any contribution for emissions during its operation. GHG emissions are intrinsically related to the fuel used to fire each unit. Hence, the release of pollutants depends on the unit efficiency and whether the fuel used is coal, natural gas or even oil, and it is consequently characterised by Fuel Consumption Coefficients (d_i, e_i) and Fuel Emission Factors $(efco_2, efno_2)$. For the present work, only CO_2 and NO_2 emissions are considered for taxation purposes, and its production factors are present in Table C.4.

Regarding the objective function (3.9), $C^{p}_{t,i}$ represents the production costs from thermal unit i due to fuel consumption, $C^{e}_{t,i}$ represents the production costs from thermal unit i due to GHG emissions, and $C^{su|sd}_{t,i}$ represents the production costs from thermal unit i due to start-up and shut-down operations. Finally, $C^{w}_{t,u}$ represents the production costs from wind unit u at time t.

$$C^{p}_{t,i} = a_i + b_i \times P_{t,i}, \;\; \forall t \in N_T, \forall i \in N_{UT} \tag{3.10}$$

In Equation (3.10), a_i and b_i define the characteristic production cost coefficients of thermal unit i related to fixed and variable fuel consumption.

$$C^{e}_{t,i} = C_{tax} \times [ef_i(f_i + g_i \times P_{t,i})], \;\; \forall t \in N_T, \forall i \in N_{UT} \tag{3.11}$$

In Equation 3.11, C_{tax} is defined by the specific penalty for emitting each one of the considered greenhouse gases (see Table C.5). Also, ef_i is the fuel emissions factor for thermal unit i, while f_i and g_i represent the fuel coefficient factors for unit i (see Table C.4).

$$C^{su|sd}_{t,i} = SU_{t,i} + SD_{t,i}, \;\; \forall t \in N_T, \forall i \in N_{UT} \tag{3.12}$$

Costs computed by Equation (3.12) bring relevance to losses caused by the starting-up $(SU_{t,i})$ and shutting-down $(SD_{t,i})$ of thermal units either when unit i gets online or offline.

$$\sum_{i=1}^{N_{UT}} V_{Pool_{t,i}} + \sum_{u=1}^{N_{UW}} V_{Pool_{t,u}} + V^{Sale}_{Bilateral_t} - V^{Purchase}_{Bilateral_t} = \sum_{i=1}^{N_{UT}} P_{t,i} + \sum_{u=1}^{N_{UW}} P_{t,u}, \;\; \forall t \in N_T \tag{3.13}$$

Constraint (3.13) expresses the required energy balance between sold energy, bought energy and produced energy, towards a null net volume.

$$0 \leq V_{Pool_{t,i}} \leq P_{t,i}, \;\; \forall t \in N_T, \forall i \in N_{UT} \tag{3.14}$$

$$0 \leq V_{Pool_{t,u}} \leq P_{t,u}, \;\; \forall t \in N_T, \forall u \in N_{UW} \tag{3.15}$$

Constraints (3.14) and (3.15) state that the maximum amount of energy produced at time t by thermal and wind units, that is sold in the pool, is capped by its hourly production. Constraints (3.16) and (3.17) define limits for hourly output oscillation from unit i by means of both *ramp-up* (RU) and *ramp-down* (RD) power.

$$P_{t,i} - P_{(t-1),i} \leq RU_i, \;\; \forall t \in N_T, \forall i \in N_{UT} \tag{3.16}$$

$$P_{(t-1),i} - P_{t,i} \leq RD_i, \;\; \forall t \in N_T, \forall i \in N_{UT} \tag{3.17}$$

$$y_{t,i} - z_{t,i} = I_{t,i} - I_{(t-1),i}, \;\; \forall t \in N_T, \forall i \in N_{UT} \tag{3.18}$$

Contraint (3.18) relates all binary variables related to the operation status of each thermal unit ($I_{t,i}$, $y_{t,i}$, $z_{t,i}$) in order to determine start-up costs, if necessary. This logical solution [60] is applied in the same way as it was applied in Section 3.3, simplifying and accelerating the computing process during optimisation.

$$P_{min_i} \leq P_{t,i} \leq P_{max_i}, \;\; \forall t \in N_T, \forall i \in N_{UT} \tag{3.19}$$

$$0 \leq P_{t,u} \leq P_{max_u}, \;\; \forall t \in N_T, \forall u \in N_{UW} \tag{3.20}$$

Constraints (3.19) and (3.20) delimit the technical output from both thermal and wind units. Finally, (3.21) and (3.22) state the binary nature of the considered variables.

$$I_{t,i}, y_{t,i}, z_{t,i} \in 0, 1, \;\; \forall t \in N_T, \forall i \in N_{UT} \tag{3.21}$$

$$I_{t,u} \in 0, 1, \;\; \forall t \in N_T, \forall u \in N_{UW} \tag{3.22}$$

3.3 Hydro and Wind Portfolio Model

Apart of thermal power generation, hydropower is the main electricity production technology technically able to operate with relative flexibility and backup the variability inherent to wind power. In fact, generation from hydro sources is usually highly controllable, especially in power plants equipped with water reservoirs, which allow big water retention and/or discharges. The considerable dispatchability of hydro power — due to high production rampages — and the possibility of using pumping systems to lift and storage water from down to upstream makes this technology the most adequate to minimise the effects of variable renewable production, for instance PV or wind power. The generation output of hydro power plants can be modelled based on technical and operational specificities of the plants, such as the head of reservoir, water discharges or the natural inflow of water into the plants' basin.

The objective function (3.23), particularly designed for a portfolio comprised of hydro and wind generation technologies, addresses the optimisation method through the maximisation of the company's profit, by computing the difference between revenues from selling energy and the costs inherent to its production.

$$\begin{aligned} z = & \sum_{t=1}^{N_T} \Bigg\{ \sum_{k=1}^{N_{UH}} \pi_{Pool_t} \times V_{Pool_{t,k}} + \sum_{u=1}^{N_{UW}} \pi_{Pool_t} \times V_{Pool_{t,u}} + \pi_{Bilateral_t}^{Sale} \times V_{Bilateral_t}^{Sale} - \\ & \pi_{Bilateral_t}^{Purchase} \times V_{Bilateral_t}^{Purchase} - \sum_{k=1}^{N_{UH}} \Bigg[I_{t,k} \times (\beta_k \times P_{t,k}) + y_{t,k} \times SU_k \Bigg] - \\ & \sum_{u=1}^{N_{UW}} \Bigg[I_{t,u} \times \beta_u \times P_{t,u} \Bigg] \Bigg\} \end{aligned} \tag{3.23}$$

The considered generation expenditures inherent to an hydro producer include both variable and start-up costs which, according to what was considered in [61], represent the following range of losses suffered by the producer at the moment of a start-up order: the loss of water during maintenance works, wear and tear of windings and mechanical equipment, malfunctions in the control equipment and loss of water during the start-up.

On the other hand, when wind production output is available and delivered to the grid, an inherent cost is inputed to the producer.

With regard to hydro units, and for the sake of a more accurate scheduling output, a set

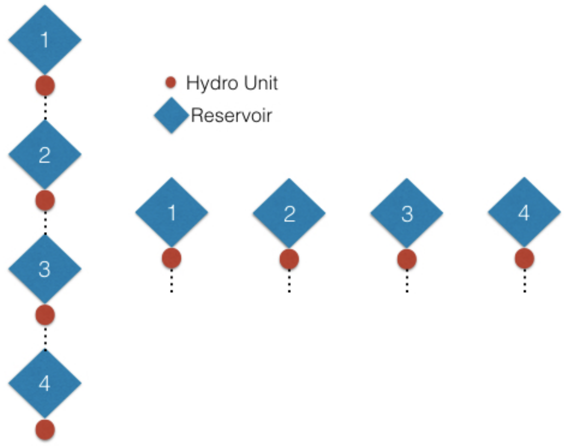

Figure 3.2: Illustration of both series coupling and standalone operation for hydro reservoirs and units

of multi-performance curves is considered to patent the close correlation between generated power and the head of the associated hydro reservoir [62]. This model also takes into account an eventual spatial coupling among reservoirs located in the same river basin (Figure 3.2). Therefore, it allows a generation scheduling optimisation of standalone hydro units as well as of units connected in series along the riverbed, having in consideration a time delay factor (τ), stating the delay of the effects of an hydro power plants's water discharge on downstream infrastructures.

$$\sum_{k=1}^{N_{UH}} V_{Pool_{t,k}} + \sum_{u=1}^{N_{UW}} V_{Pool_{t,u}} + V_{Bilateral_t}^{Sale} = \sum_{k=1}^{N_{UH}} P_{t,k} + \sum_{u=1}^{N_{UW}} P_{t,u} - V_{Bilateral_t}^{Purchase}, \quad \forall t \in N_T \quad (3.24)$$

Constraint (3.24) defines a compulsory energy balance, where hourly sold energy — whether bilaterally or in pool — is forced to have equal value to the energy hourly produced plus the eventual energy volume bought via bilateral contracts with retailers and/or other generation companies. In other words, the constraint states equality between the transacted energy net volumes and the generated electrical energy required to supply such needs. As mentioned before, the method followed by [63] uses a set of curves to bind water discharges and power outputs.

As it can be seen in Figure 3.3, each three-dimensional curve relates power output, water discharge and the head of the reservoir. Constraint (3.25) assure the correct hourly performance curve assignment considering the existing water volume $v_{t,k}$ in each reservoir k at t.

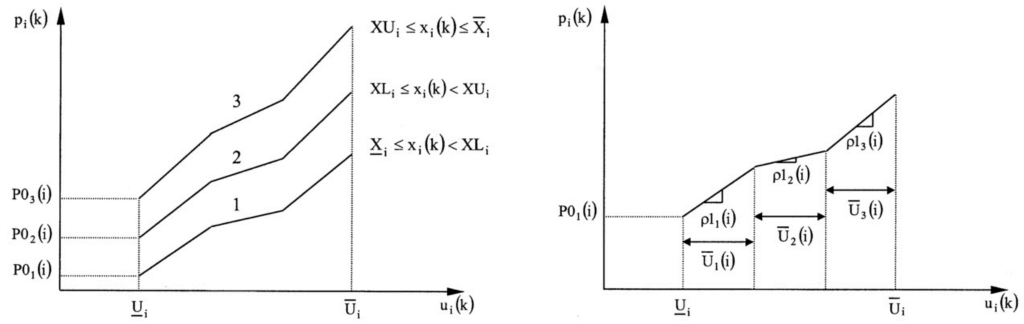

Figure 3.3: Performance curves for plant i and discretisation of curve 1 (Power vs Water Discharge) [63]

$$
\begin{aligned}
& v_{t,k} \geq VL_k[d_{1_{t,k}} - d_{2_{t,k}}] + VU_k \times d_{2_{t,k}}, \;\; \forall t \in N_T, \forall k \in N_{UH} \\
& v_{t,k} \leq V_k^{max} \times d_{2_{t,k}} + VL_k[1 - d_{1_{t,k}}] + VU_k[d_{1_{t,k}} - d_{2_{t,k}}], \;\; \forall t \in N_T, \forall k \in N_{UH} \\
& d_{1_{t,k}} \geq d_{2_{t,k}}, \;\; \forall t \in N_T, \forall k \in N_{UH} \\
& v_{t,k} \geq V_k^{min}, \;\; \forall t \in N_T, \forall k \in N_{UH}
\end{aligned}
\tag{3.25}
$$

Hereupon, if at a given period t, the content of reservoir k, $v_{t,k}$, is bellow the low level limit VL_k (XL_i in Figure 3.3), the energy production output shall be ruled by performance Curve 1. If $v_{t,k}$ is located between the low level and the upper level VU_k (XU_i in Figure 3.3), then Curve 2 is selected. On the other hand, if the reservoir content is above the upper level limit, Curve 3 is selected and unit k operates according to the higher performance curve. Binary values, $d_{1_{t,k}}$ and $d_{2_{t,k}}$, operate as a switch, used to select the right curve:

$$
\begin{cases}
Performance \;\; Curve\, 1 & if \;\; d_{1_{t,k}} = 0 \wedge d_{2_{t,k}} = 0; \\
Performance \;\; Curve\, 2 & if \;\; d_{1_{t,k}} = 1 \wedge d_{2_{t,k}} = 0; \\
Performance \;\; Curve\, 3 & if \;\; d_{1_{t,k}} = 1 \wedge d_{2_{t,k}} = 1;
\end{cases}
$$

Formulation of the non-concave unit performance curves is made as shown by constraints (3.26) to (3.31). Constraint (3.26) represents the construction of Curve 1, designed for operations with low level reservoir contents. Since low water contents presupposes $d_{1_{t,k}} = 0$ and $d_{2_{t,k}} = 0$, the output power is, then, equal to the minimum power plus the blocks of the lower-level piecewise linear curve. This situation is analogous to (3.27), for Curve 2, and to (3.28), for Curve 3.

$$
\begin{aligned}
&P_{t,k} - P0_{1_k} \times I_{t,k} - \sum_{l=1}^{L} u_{l_{t,k}} \times \rho 1_{l_k} - P_k[d_{1_{t,k}} + d_{2_{t,k}}] \leq 0, \;\; \forall t \in N_T, \forall k \in N_{UH} \\
&P_{t,k} - P0_{1_k} \times I_{t,k} - \sum_{l=1}^{L} u_{l_{t,k}} \times \rho 1_{l_k} + P_k[d_{1_{t,k}} + d_{2_{t,k}}] \geq 0, \;\; \forall t \in N_T, \forall k \in N_{UH}
\end{aligned}
\tag{3.26}
$$

$$
\begin{aligned}
&P_{t,k} - P0_{2_k} \times I_{t,k} - \sum_{l=1}^{L} u_{l_{t,k}} \times \rho 2_{l_k} - P_k[1 - d_{1_{t,k}} + d_{2_{t,k}}] \leq 0, \;\; \forall t \in N_T, \forall k \in N_{UH} \\
&P_{t,k} - P0_{2_k} \times I_{t,k} - \sum_{l=1}^{L} u_{l_{t,k}} \times \rho 2_{l_k} + P_k[1 - d_{1_{t,k}} + d_{2_{t,k}}] \geq 0, \;\; \forall t \in N_T, \forall k \in N_{UH}
\end{aligned}
\tag{3.27}
$$

$$
\begin{aligned}
&P_{t,k} - P0_{3_k} \times I_{t,k} - \sum_{l=1}^{L} u_{l_{t,k}} \times \rho 3_{l_k} - P_k[2 - d_{1_{t,k}} - d_{2_{t,k}}] \leq 0, \;\; \forall t \in N_T, \forall k \in N_{UH} \\
&P_{t,k} - P0_{3_k} \times I_{t,k} - \sum_{l=1}^{L} u_{l_{t,k}} \times \rho 3_{l_k} + P_k[2 - d_{1_{t,k}} - d_{2_{t,k}}] \geq 0, \;\; \forall t \in N_T, \forall k \in N_{UH}
\end{aligned}
\tag{3.28}
$$

$$
u_{t,k} = \sum_{[l=1]}^{L} u_{l_{t,k}} + U_{min_k} \times I_{t,k}, \;\; \forall t \in N_T, \forall k \in N_{UH} \tag{3.29}
$$

$$
\begin{aligned}
&u_{1_{t,k}} \leq U_{1_t}^{max} \times I_{t,k}, \;\; \forall t \in N_T, \forall k \in N_{UH} \\
&u_{1_{t,k}} \geq U_{1_t}^{max} \times w_{1_{t,k}}, \;\; \forall t \in N_T, \forall k \in N_{UH}
\end{aligned}
\tag{3.30}
$$

$$
\begin{aligned}
&u_{l_{t,k}} \leq U_{l_t}^{max} \times w_{l-1_{t,k}}, \;\; \forall t \in N_T, \forall k \in N_{UH}, \forall l \in L \\
&u_{1_{t,k}} \geq U_{l_t}^{max} \times w_{l_{t,k}}, \;\; \forall t \in N_T, \forall k \in N_{UH}, \forall l \in L
\end{aligned}
\tag{3.31}
$$

Blocks for each piecewise linear curve are defined through constraint (3.29), stating that the total water discharged volumes are equal to the sum of individual blocks' water volumes of a given performance curve. The sum of blocks is managed by the binary variable $w_{l_{t,k}}$, which is equal to 1, if the water discharge of plant k at time t has exceeded block l, and 0 otherwise [63, 64].

$$
v_{t,k} = v_{t-1,k} + W_{t,k} + M \times [u_{(t-\tau),k-1} - u_{t,k}], \;\; \forall t \in N_T, \forall k \in N_{UH} \tag{3.32}
$$

where $k-1$ refers to the immediately upstream hydro unit.

Constraint (3.32) ensure a proper water balance of this system. If no coupling among hydro units exists, the optimisation of their generation scheduling is computed as if they were isolated (in parallel), meaning that the water balance accounts only the hourly inflow of the reservoir, and the discharged water volume during the operation of each hydro power plant. In a series coupling scenario, the hourly water content of the unit's reservoir k is additionally affected by water discharges of the upstream unit $(k-1)$ with a delay of τ hours.

$$y_{t,k} - z_{t,k} = I_{t,k} - I_{t-1,k}, \ \ \forall t \in N_T, \forall k \in N_{UH} \tag{3.33}$$

Constraint (3.33) relates all binary variables related to the operation status of each hydro unit ($I_{t,k}$, $y_{t,k}$ $z_{t,k}$) in order to compute start-up costs. For instance, if an hydro unit k is offline at a period $(t-1)$, $(I_{t-1,k} = 0)$, and online at period t, $(I_{t,k} = 1)$, $y_{t,k}$ is forced to assume the value 1, indicating that a start-up has occurred, which reflects a cost for the producer. According to [60], this relation has also proved its ability to simplify and accelerate the computing process during the scheduling optimisation.

$$\begin{aligned} &I_{t,k}, y_{t,k}, z_{t,k}, d_{1_{t,k}}, d_{2_{t,k}} \in \{0,1\}, \ \ \forall t \in N_T, \forall k \in N_{UH} \\ &w_{l_{t,k}} \in \{0,1\}, \ \ \forall t \in N_T, \forall k \in N_{UH}, \forall l \in L \end{aligned} \tag{3.34}$$

$$P_{t,i}, u_{t,k}, v_{t,k} \geq 0, \ \ \forall t \in N_T, \forall k \in N_{UH} \tag{3.35}$$

$$u_{l_{t,k}} \geq 0, \ \ \forall t \in N_T, \forall k \in N_{UH}, \forall l \in L \tag{3.36}$$

Equation (3.34) define the logical dimension of the remaining variables used in this problem solving algorithm. Also, $I_{t,k}$, $y_{t,k}$, $z_{t,k}$, $d_{1_{t,k}}$, $d_{2_{t,k}}$ and $w_{l_{t,k}}$ are defined as binary variables, assuming a switch-like function on the optimisation. Equations (3.35) and (3.36) establish the impossibility of any production volume, discharge volume or reservoir volume to assume a negative value.

The Multi-agent Simulator MAN-REM: Initial and Extended Versions

4.1 The Initial Simulator

The MAN-REM is a JAVA-based multi-agent simulator developed by LNEG over the last years. Its characteristics are mostly derived from the multi-agent platform JADE, aiming to show and carefully study all the interactions and events taking place in a real-world electricity market situation. This tool was designed to provide simulation capacities to mimic, for instance, the real environment of an electricity pool market. Additionally, due to JADE's platform, interaction among several market players can be modelled and simulated.

The current version of the simulator allows the recreation of an electricity pool platform both in the daily and intra-daily markets, based on two main market models, namely the *system marginal price* (SMP) and the *locational marginal price* (LMP). These models allow a complete analysis of both the day-ahead market and the adjustment market, essential to the proper functioning of the electricity sector. To perform the simulations and extract the consequent results, a sequence of processes needs to be followed with the purpose of configuring the agents, the market model under appreciation, the pricing algorithm and some characteristics of the power grid.

The main window of the MAN-REM (Figure 4.1) was designed to provide an essential overview of the market agents, which are about to interact in a virtual market. Along side the left and right borders, the name of each market player is added and also detailed personal information is sequentially introduced by the user.

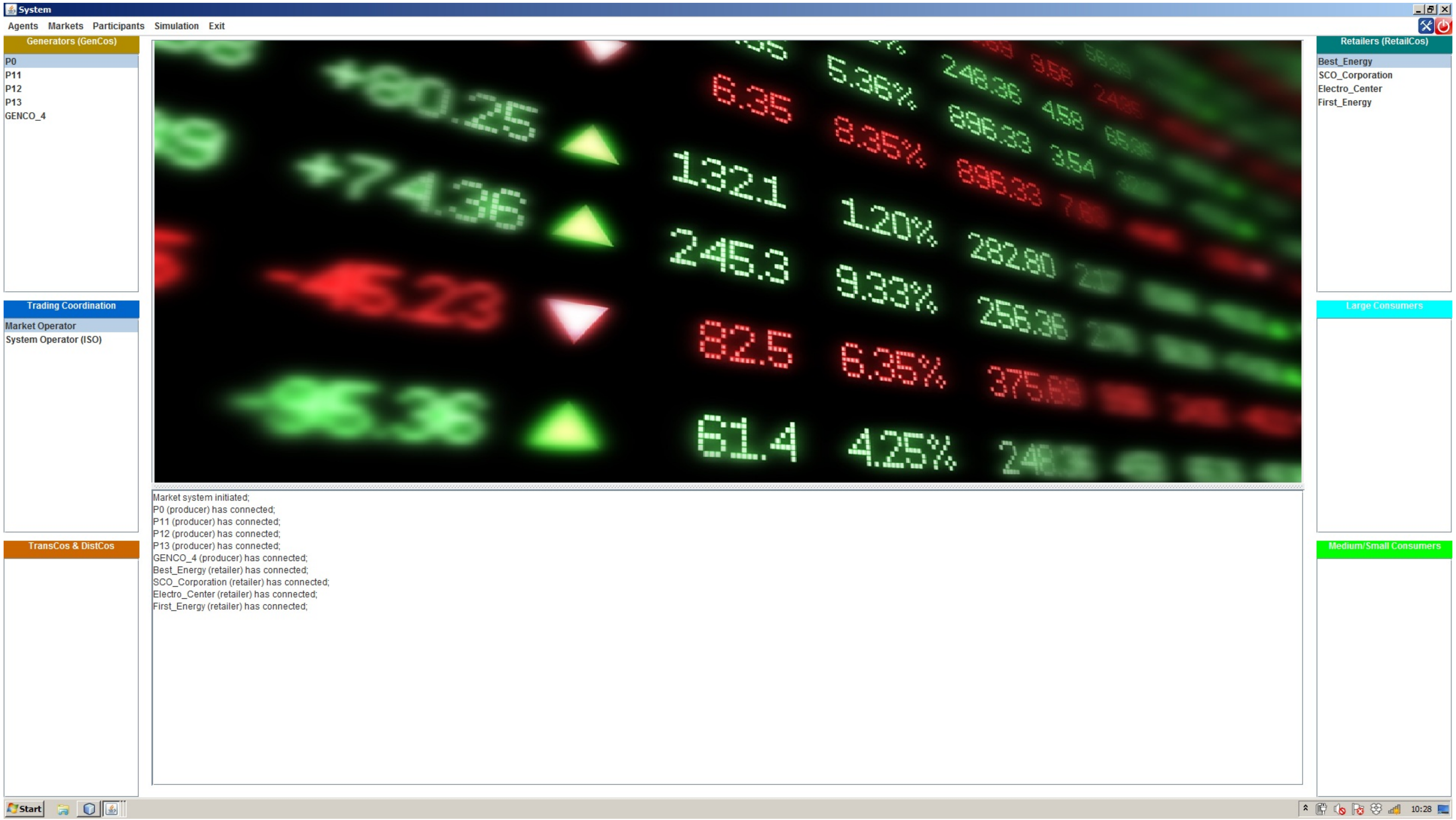

Figure 4.1: MAN-REM simulator: home screen

4.1.1 Participants: Agents Menu

Currently, the software is comprised of three categories of agents, which can interact with one another, notably *Generation Companies*, *Retail Companies* and *End-Use Costumers*. As a first step during the creation of a new agent (Figure 4.2), whether a generation company (GenCo agent), a retailer or a consumer, one is invited to provide some generic informations about it. In the case of adding a GenCo — in the "*Enter GenCo*" window (Figure 4.3) — apart from the *GenCo Name*, all input details are indicative. This process formalises the creation of a new production agent that could be subsequently called to interact in a market simulation.

4.1.2 Market Models: Markets Menu

The "Markets Menu" allows the user to select the market model which will rule the desired simulation. This menu provides options for the energy market on the stock exchange and the bilateral trading, such as the Energy Markets, Forward Market or Futures Market. Concerning the Energy Markets, either the Day-ahead Market or the Intraday Market can be simulated using two different bidding algorithms.

System marginal price (SMP)

The *system marginal price* algorithm, developed by team of the MAN-REM project, and added to the system, allows market simulation stock. The structure of the offers, as mentioned, comprises the hourly time of each offer, the purchase/sale price and the volume of energy to trade (Figure 4.4). Unlike the local marginal price algorithm, presented below, the SMP does not include network specifications, meaning that it does not have the ability to check for bottlenecks. The SMP forms the basis of the algorithms used by some real-world markets, including MIBEL, to define the prices of the daily and intraday markets.

Locational marginal price (LMP)

The *locational marginal price* algorithm allows market simulation on the stock exchange, and can assign a price per hour to every single power grid node. Its structure, as mentioned, includes a greater number of data, compared with the *single marginal price* algorithm, presenting differences regarding the structure of the offers, composed of an initial price and a slope variable, representing the elasticity of the agent to the market price, positively influencing the increased bid sale price. For a more detailed description of the system, the interested reader is referred to [10, 12, 65].

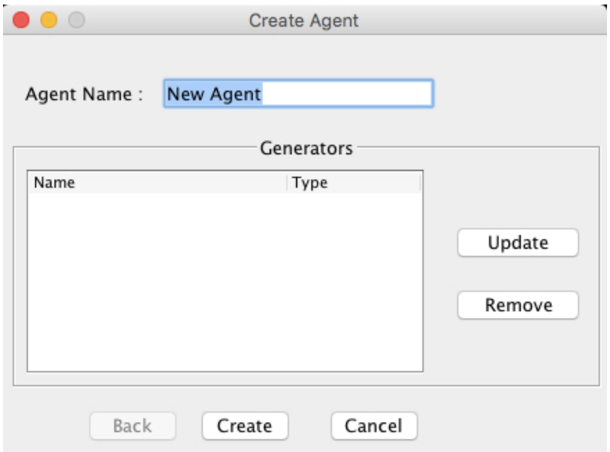

Figure 4.2: Window to create a new agent

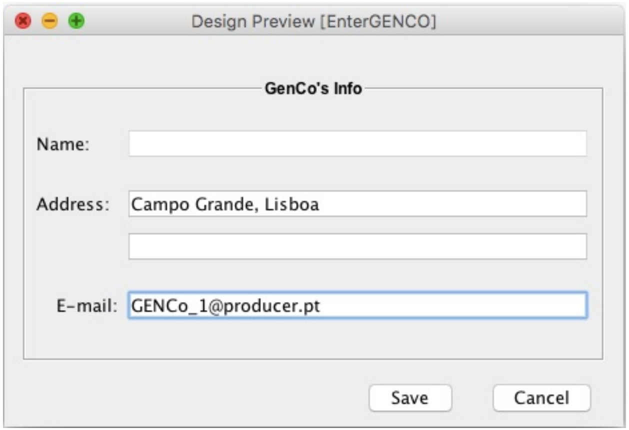

Figure 4.3: Add a new production agent: GenCo personal info window

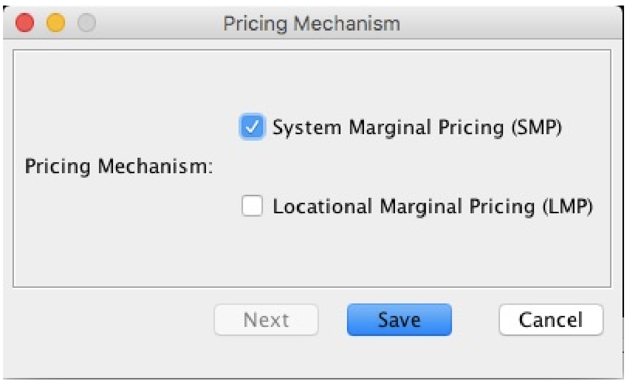

Figure 4.4: Pricing mechanisms window

4.2 The Extended MAN-REM Simulator

In order to provide a self-scheduling tool, several new crucial interface windows were added to the existing software, representing a significant share of the work time invested in this project, which was reflected in more than 12 000 programming JAVA code lines, developed on NetBeans IDE.

Since all generation units were, in their former version, characterised simply by their maximum and minimum output power, and due to some complexity of the input data required by the self-scheduling models presented in the previous chapter, a new and larger virtual database for technical specifications was created, in order to store all the necessary details.

Additionally, a new set of interface windows was added to the simulator, allowing one to declare all the required information regarding an agent's portfolio. Moreover, new upload functionalities were added to *MAN-REM* to provide information on production forecasts concerning wind farms or even on hourly water inflows in reservoirs associated to hydro power plants. The scheduling process added to the software will be explained in detail further on.

4.2.1 Portfolio Construction

After the creation of a new GenCo agent, the following step is its allocation to a portfolio of power plants. The "*Add Portfolio*" window, shown in Figure 4.5, is the starting point for the portfolio construction. As can be seen, the user can sequentially add new generation units, proceed to further update existing power plants, or even remove some of them. Summarised data about the current portfolio is made available through the data table of the window.

Pressing the "*Add*" button of the "*Add Portfolio*" window initiates the process of adding a new generation unit, showing the "*Preliminary Information*" window (Figure 4.6). As shown, the type of this window allows the user to provide general technical specifications, transversal to all technologies, such as *Technology*, *Fuel*, *Minimum Power* and *Maximum Power*. An unit *ID* can also be provided for the propose of identification.

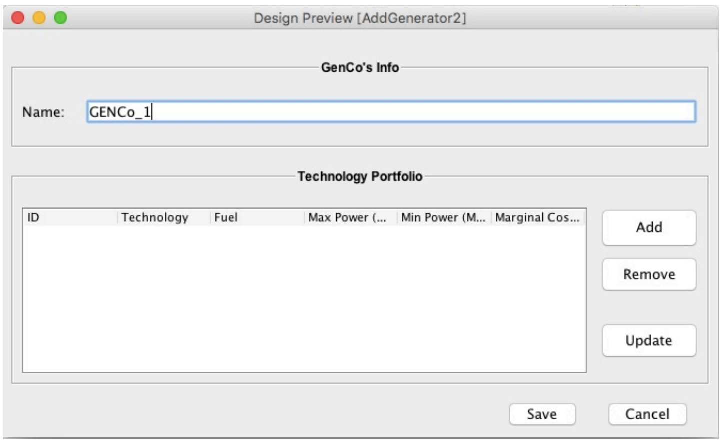

Figure 4.5: Add a new production agent: add portfolio window

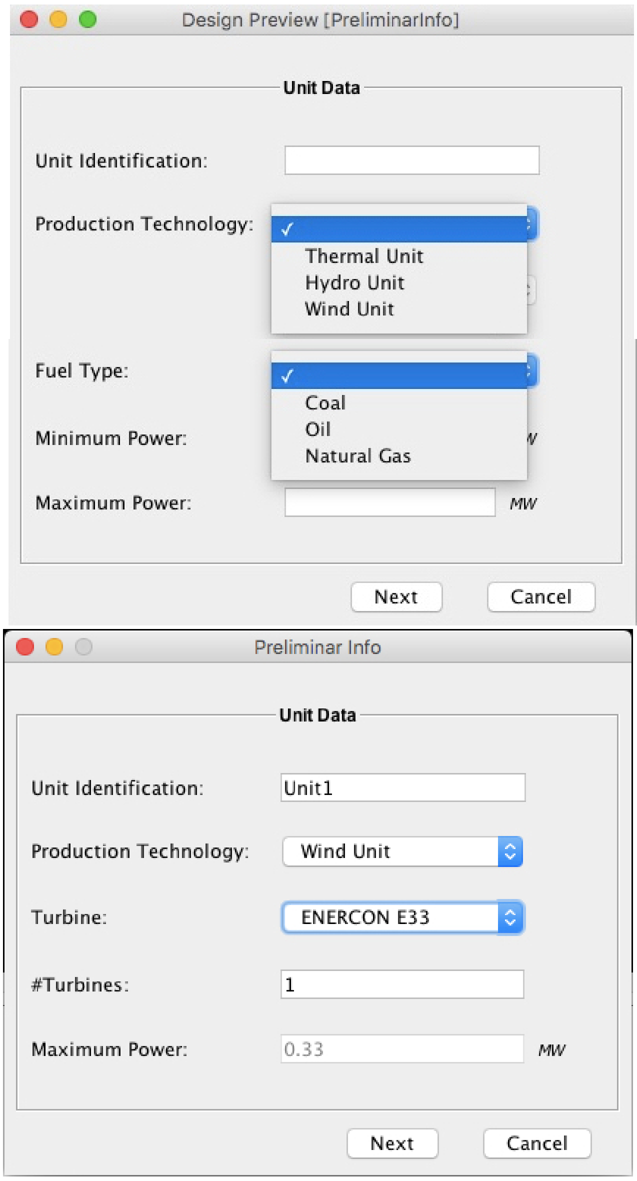

Figure 4.6: Adding a new production agent: preliminary information windows

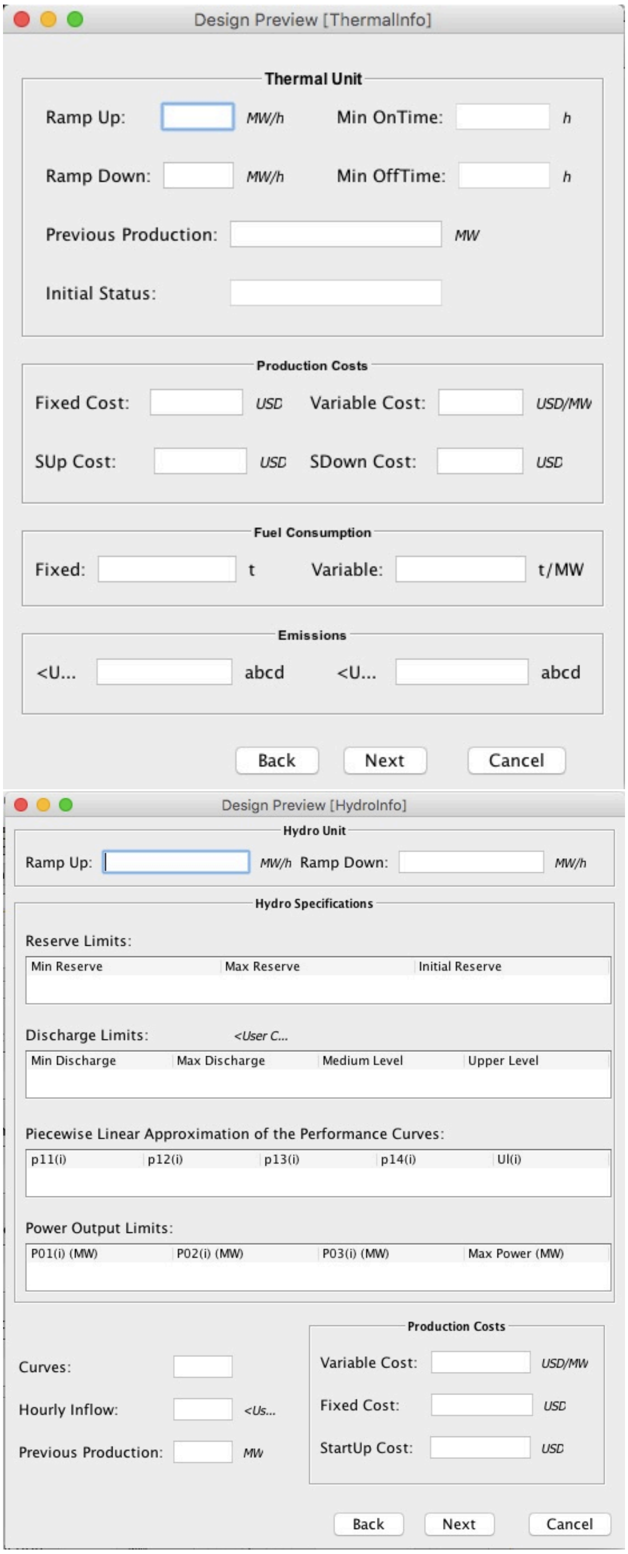

Figure 4.7: Adding a new production agent: add new thermal/hydro unit to GenCo windows

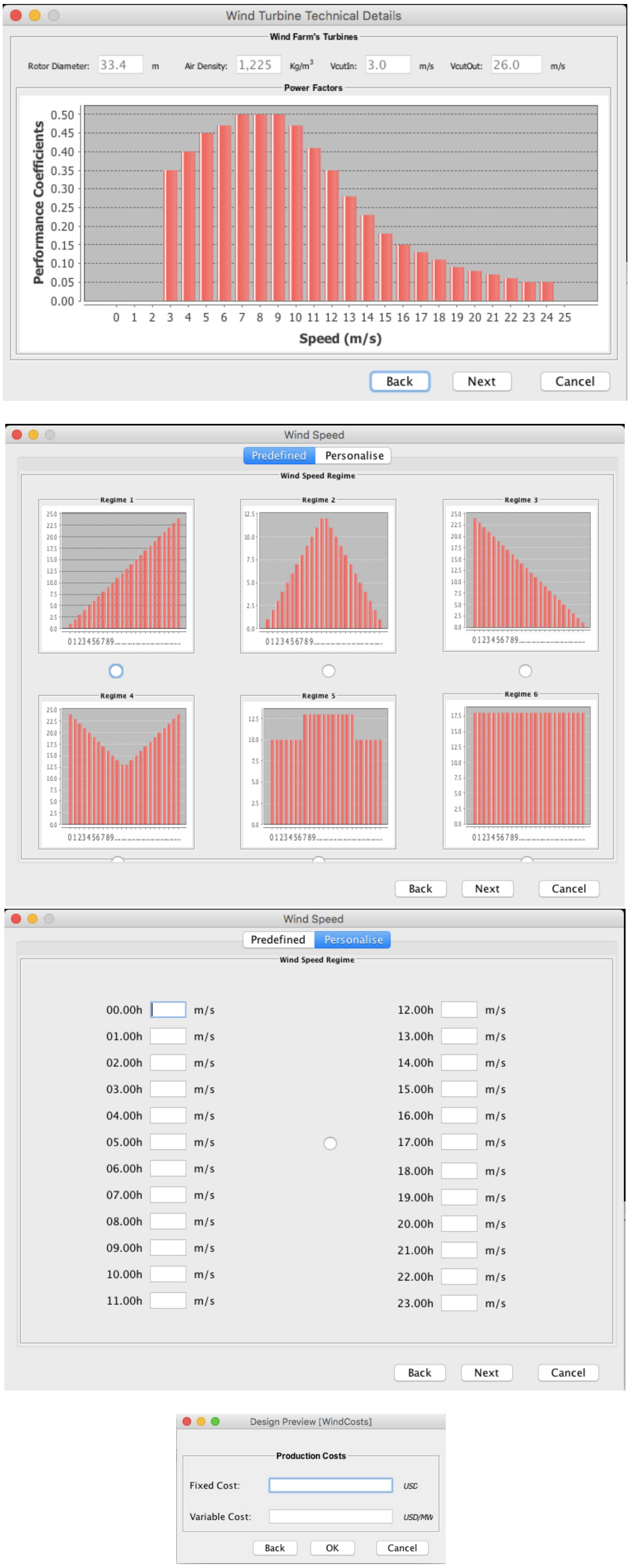

Figure 4.8: Adding a new production agent: add new wind unit to GenCo windows

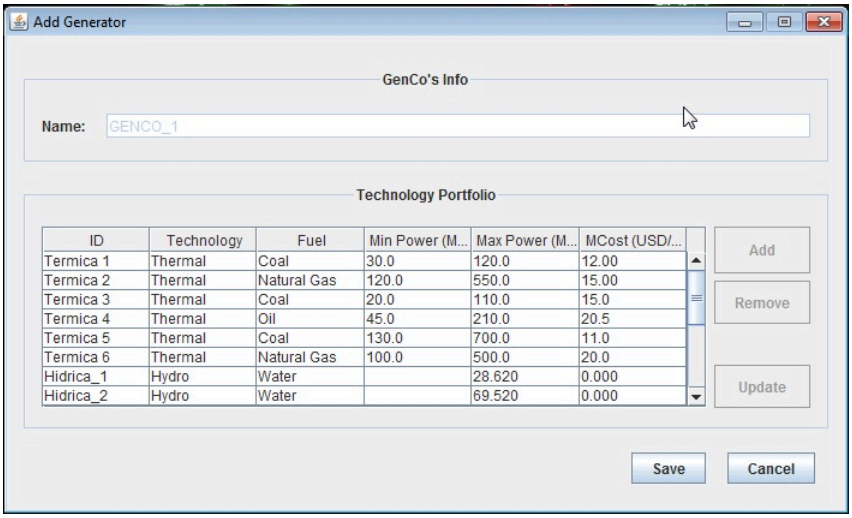

Figure 4.9: Scheduling a GenCo's portfolio: add portfolio window (final)

Three main production technologies were considered: thermal, hydro and wind. However, fuel distinctions are accounted when it comes to thermal technologies, permitting to specify the firing type of each power plant. For the wind case, an existing database of wind turbines is available and the user can simply select the desired model. Additionally, the user is required to provide the number of wind generators that are part of the wind farm.

From here, the process of adding of new generation units suffers a ramification according to the selected technology. Therefore, if *Thermal Unit* is selected in the "*Technology*" box, the user is further invited to proceed to the "*Thermal Unit Information*" window and fill the remaining thermal-related technical details. Likewise, if the *Hydro Unit* option is selected, the user is redirected to the "*Hydro Unit Information*" window or, in the case of the *Wind Unit*, to the "*Wind Turbine Technical Details*" window, where technical specifications of the turbines are displayed. In particular, the "*Wind Speed Regime*" window, where hourly wind speeds are defined to further compute wind farm's output production, and the "*Wind Unit Cost Information*" window, where eventual fixed and variable production costs (see Figure 4.8).

During the construction process of a GenCo's portfolio, the user has the chance to overview the composition of the current generation infrastructure. Once this process is completed, the data inserted can be saved by clicking "*Save*" in the "*Add Portfolio*" window (Figure 4.9), leading the user to the window where forecasts of prices of pool and bilateral contracts markets are submitted to the system (Figure 4.10), before finishing the first stage towards a further market simulation.

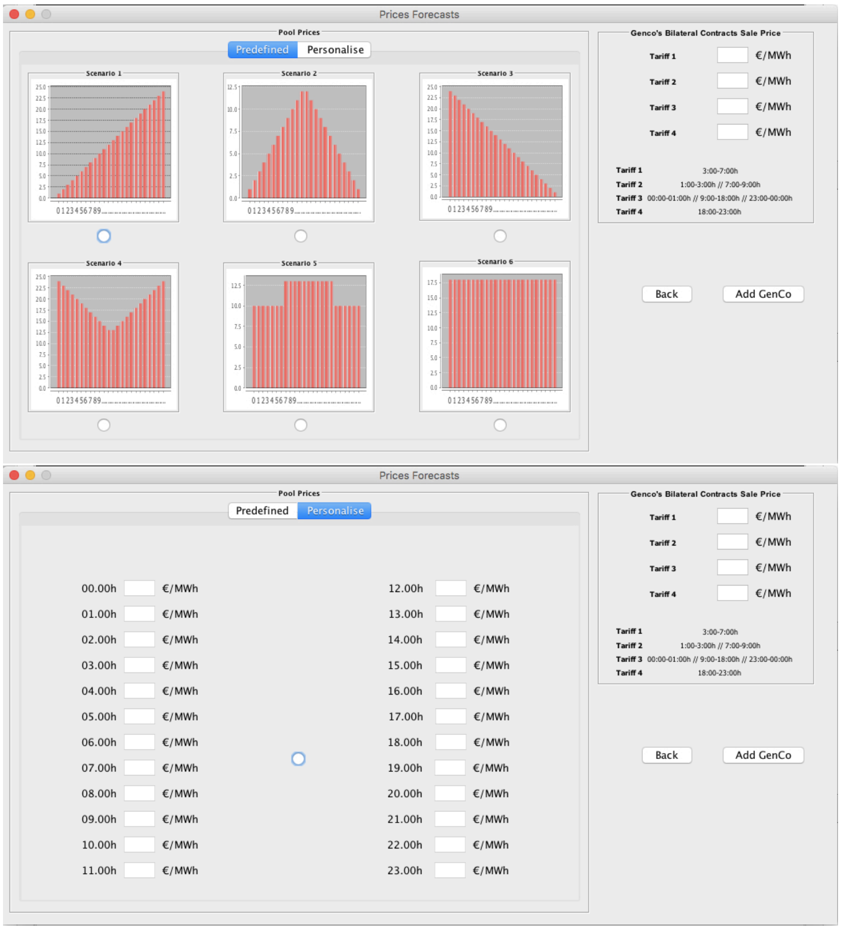

Figure 4.10: Adding a new production agent: set GenCo's price forecasts window

4.2.2 Scheduling Process

The second stage of market simulation, as adherent as possible to the reality, is the GenCo's self-scheduling of production and the subsequent electricity market settlement. Despite the fact that both objectives and methods of a self-scheduling process may vary from company to company, all the considered models integrated in MAN-REM, as discussed in Subsections 3.1, 3.3 and 3.2, address this problem by optimising the financial profit from selling energy in the market, through the maximisation of the net balance of revenues and costs. Accordingly, a "*Unit Selection*" window was created, so that users can specify the scheduling optimisation process details (Figure 4.11).

After choosing the desired generation agent for the scheduling optimisation, the user will have at his/her disposal a list of the electricity generation units associated to it. As discussed in Chapter 3, each optimisation method has the focus on a particular portfolio composition and, therefore, scheduling models should be chosen with regard to the selected portfolio.

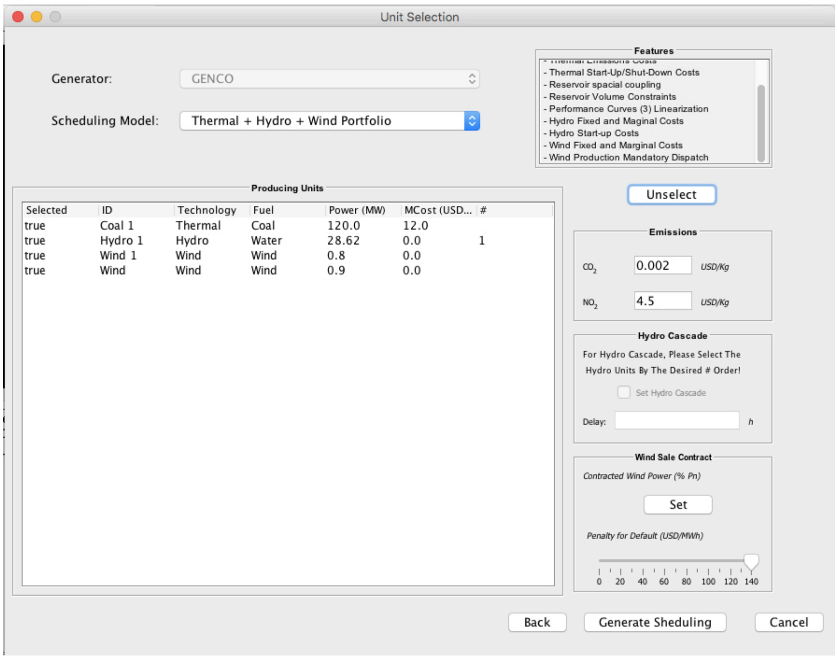

Figure 4.11: Scheduling a GenCo's portfolio: choosing model window

Hence, even if a given GenCo owns three different generation technologies, if the "Thermal portfolio" model is selected, the simulator immediately runs a filter, removing all other technologies from the table, disabling its usage. This "filtering" mechanism works in the same manner for the remaining models, in order to display only plausible unit options, according to the selected model.

The "*Select/Unselect*" button was designed to add units to the optimisation process. This step allows the user to pick, among the available portfolio, the generation units that are to be scheduled and those which, by any reason, are not.

Depending on the selected scheduling model, more input details may be necessary for the optimisation to be successful. For instance, if the "*Hydro and Wind Portfolio*" model is selected, the "*Hydro Cascade*" panel is enabled and the user has the possibility to configure a sequential spacial coupling among the selected group of hydro units. In this case, a time delay, foreseen by the "*Hydro and Wind Portfolio*" model, is required, defining the time needed for the downstream reservoir to be affected by the operation of the upstream hydro unit.

Similarly, data for the "*Thermal and Wind Portfolio*" model concerning the taxation over greenhouse emissions (CO_2 and NO_2) should be inserted, if this model is selected, and then the "*Emissions*" panel is enabled.

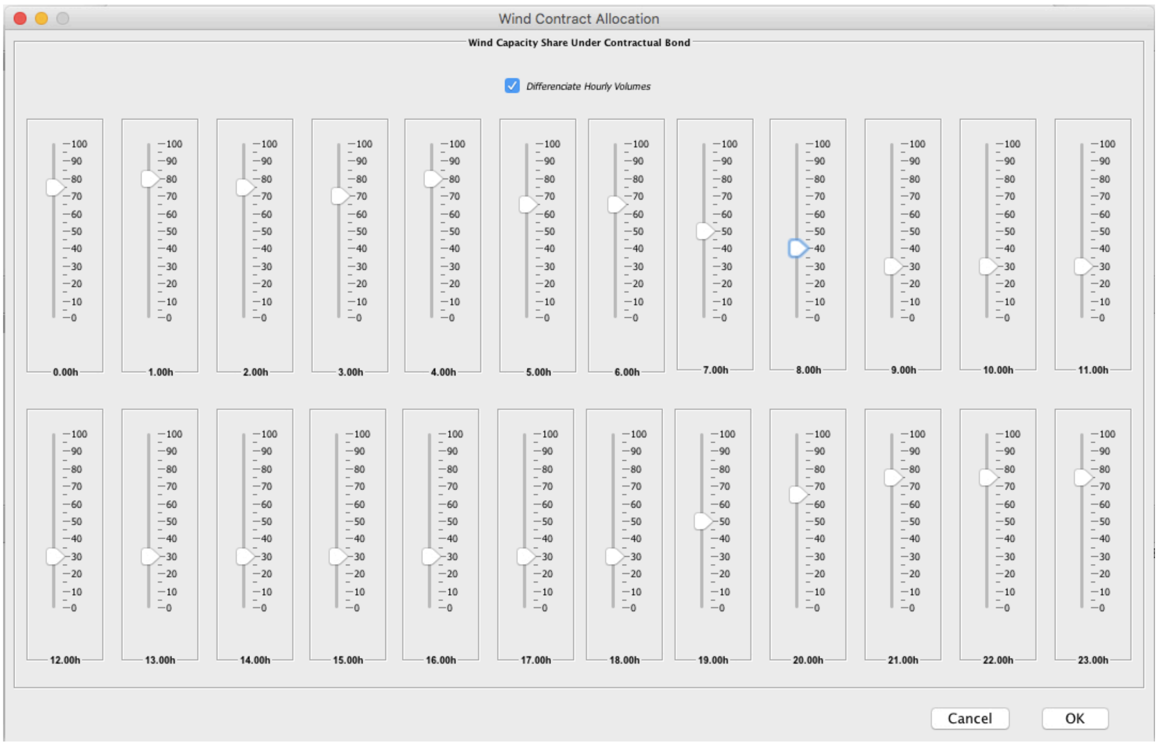

Figure 4.12: Scheduling a GenCo's portfolio: set pre-sold energy volumes window

The "*Contractual Allocation of Wind Power*" window (Figure 4.12) was especially created to support the insertion of a new type of input required by the new "*Thermal, Hydro and Wind Portfolio*" scheduling model. In this case, the user has the option to set an hourly share of the wind farms' total capacity that is already sold through bilateral contracts even before the start of the day-ahead market session. Additionally, since the electricity volume sold *a priori* can or cannot be effectively produced due to the variability of the wind resource, it is essencial to define a penalty, charged for each energy unit not delivered.

Once the "*Generate Scheduling*" option is selected, the model can run and the optimisation function computed by LP_SOLVE 5.5, a freeware Mixed Integer Linear Programming (MILP) solver, developed at the Eindhoven University of Technology, which solves pure linear, (mixed) integer/binary, semi-continuous and special ordered sets models [66, 67]. In other words, all the models described in the previous chapter were implemented in the MAN-REM system, using the JAVA programming language, and LP_SOLVE 5.5.

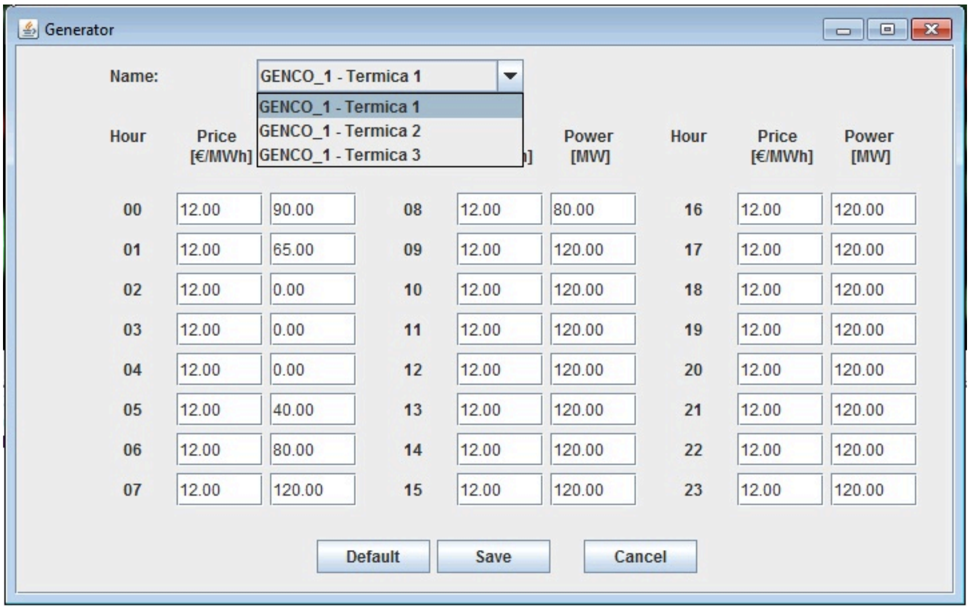

Figure 4.13: Scheduling a GenCo's portfolio: place pool bids windows

4.2.3 Scheduling Results Data

Output data is summarised on the "*Scheduling Output*" window. As depicted in Figure 4.14, four charts provide all the output information computed by the selected scheduling model. Here, after checking the suggested hourly energy settlement, scheduled production and forecasted profit and comparing both prices and costs[1], the user has the possibility to agree with the presented solution and *Save* the scheduling data or, on the other hand, reject (*Discard*) it and restart the scheduling process with further desired changes in the portfolio.

Agreeing on the scheduling optimisation output means that all bids are sent to the market operator. Depending on the number (n) of generation units scheduled, a GenCo places n bids into the pool market. Each bid, placed separately for each unit, is embodied by an energy volume and a price, which is equal to the respective marginal cost inherent to its generation unit (Figure 4.13).

Once the self-scheduling process is finished, more generation competitors can join the market and have their portfolios scheduled, increasing the pool competitiveness.

[1] The reason why the marginal costs of the unit "Termica 2" are not visible in the "Prices & Costs" window tab is the overlapping with the line of "Termica 2" whose marginal costs have the same value.

Figure 4.14: Scheduling a GenCo's portfolio: scheduling output window

4.2.4 Additional Developments

Apart from the main developments indicated above, other features were also deployed and implemented in this new version of the MAN-REM simulator:

Load "Generation Agent and Portfolio"

Due to some complexity and lengthy of the process required to add a new generation agent and its portfolio from scratch, a *load* function was created so that users could gradually create a market environment scenario much more expeditiously. Consequently, this new software version has available a *Genco Template*, under the form of an EXCEL spreadsheet, that can be used as a database to be uploaded and, instantly, construct a new generation agent.

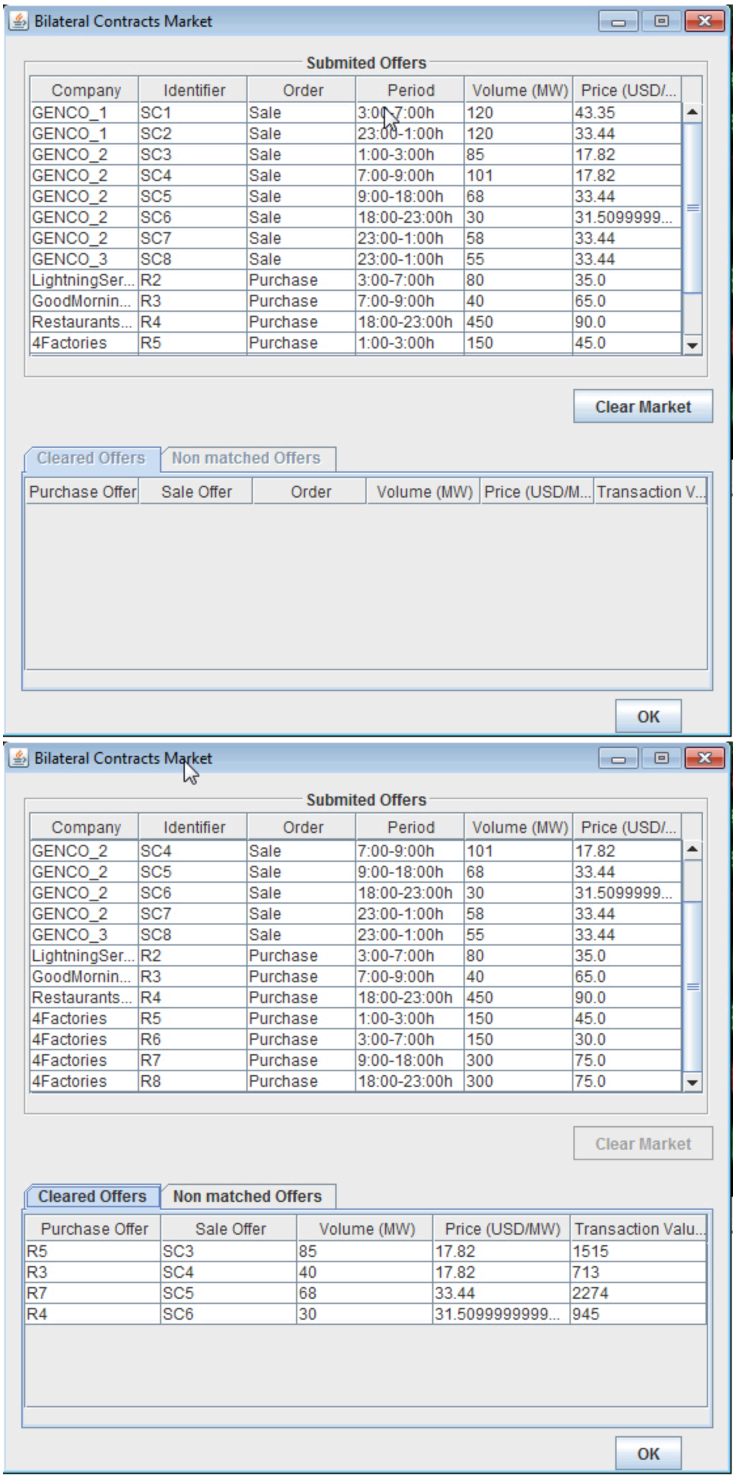

Figure 4.15: Over-the-counter contracts clearing tool

Electronic Bilateral Trading Mechanism

Despite the fact that MAN-REM already has an agent-based mechanism of trading for the bilateral contracts market, such tool is a negotiation-based trading platform, which involves negotiation between agents — buyers and sellers — according to their goals and adopted strategies.

The "Electronic Trading Mechanism", as discussed in Subsubsection 2.3.2, is an entry-order merit system where, once an order is received, the software runs the exchange, checking and looking up for a matching offer. As such solution did not exist in the previous software version, a contract clearing platform was developed and added to the MAN-REM in order to provide a new market tool. Figure 4.15 depicts this trading platform which arranges all placed offers according to their entry order. Once the clearing procedure is started, the system initiates a loop-based method and compares the first offer, at the top, with the following offers. If a match is found, both offers are cleared at the sale price. Moreover, if one of the matched offers is not completely fulfilled in its power volume, the remaining power is kept in the market for a further match until it is totally cleared.

Production Scheduling: Case Studies

The following case studies aim to demonstrate at some level the relevance of the self-scheduling models added to the simulator and the MAN-REM's output data. Simultaneously, this demonstration process will also allow to evaluate the correct functioning and pertinence of all the fifteen new windows that were programmed and embodied in the simulator along this work. Hence, this chapter will be essentially a bipartite exercise where the responsivity of the models to the *GenCo*'s target market prices will be assessed (Case Study I) and the effect of variable renewable electricity production on pool prices will be demonstrated (Case Study II).

For the first case study, two simulations of the day-ahead electricity pool market were run for each scheduling model to be tested, totalling six market simulations (3 models $\times$ 2 simulations). Hereupon, a set of generation agents, holding different unit portfolios, and of retail agents, were used in order to mimic a competitive power market. Furthermore, a single sale bid, comprised of twenty-four prices and volumes, was sent by an additional generation agent. After all the sale and purchase bids were communicated to the market operator, the pool mechanism was run and the market cleared, yielding the transacted volumes and the market clearing prices. Aiming to test the coherence of each model, the single bid referred above is replaced by another one, calculated using the self-scheduling optimisation and having the MCP from the previous session as price target. Both output values were then compared.

The second case study aims at analysing the effect of high variable production from renewables — wind, in this particular case — on pool prices, and requires only two market simulations, where using the same set of market agents as in the prior simulations, the wind speeds forecasted and provided as an input to the model are substantially antagonistic, representing each of them a windy day and a low-wind day. For both wind speed scenarios, the market is run and the yielded MCP compared.

5.1 Case Study I: Demonstration of the Optimisation Models

In order to demonstrate the functioning of the self-scheduling optimisation models, added to the MAN-REM extended version as a result of this work, and analyse their output data, the system will be subject to some testing examination.

Because this process requires consecutive pool market simulations, a standard set of market players was defined, meaning that certain producers and retailers are kept constant throughout this case study. Consequently, eleven bids from three different generation companies — P2, P3 and P4 — represent a static group of sale offerings to the market, which are submitted to the MAN-REM's virtual market operator and ensure enough market liquidity.

As depicted in Figure 5.1, an additional sale agent — $P0_{\{T,T\&W,H\&W\}}$ — was included in the market and whose portfolio is dependent on the optimisation model being analysed — "*Thermal Portfolio*", "*Thermal and Wind Portfolio*" and "*Hydro and Wind Portfolio*", respectively. Each offering consists of a certain energy volume and marginal cost associated with the generation unit where it is produced. For the present exercise, it was decided that GenCos would bid their nameplate capacity over the twenty-four hours period which constitutes the day-ahead pool market span (Figure 5.2). The $P0_{\{T,T\&W,H\&W\}}$ producers' bids are defined "manually", without the intervention of any system to support the management of production and operation of the generation portfolio.

Likewise, eleven standard purchase offerings from retail companies — *Best Energy*, *SCO Corporation*, *Electro Center* and *First Energy* — were considered, providing considerable competition to the market. Contrary to the generation companies' bids, purchase offerings, based on [68] are variable in volume and price throughout the day (Figure 5.3), picturing consumption profiles from a wide range of industrial, domestic and commercial electricity consumers (further details are shown in Tables B.1 – B.4).

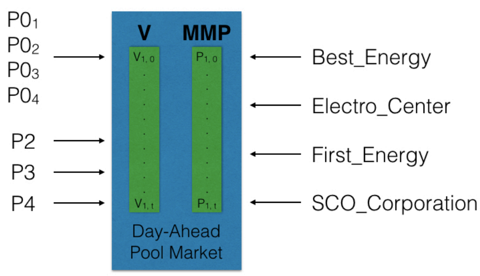

Figure 5.1: Scheme of market agents entering the market (first market simulation)

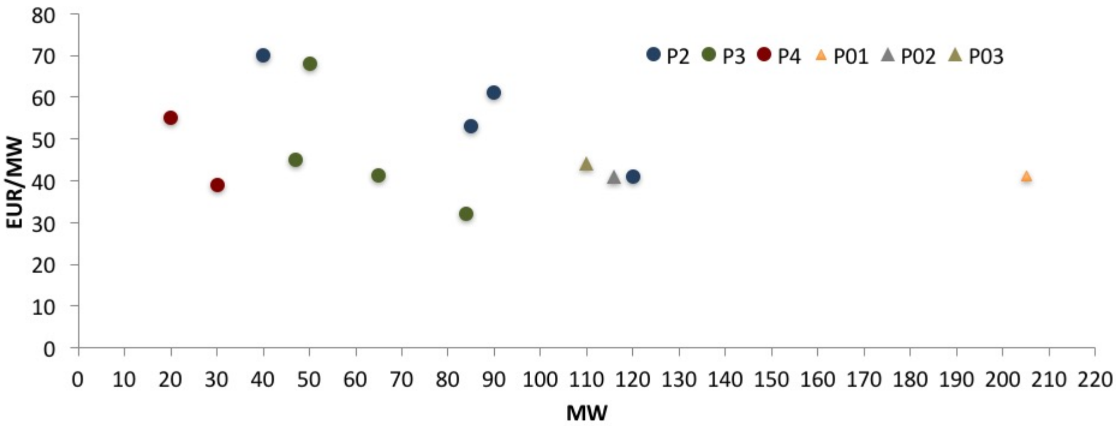

Figure 5.2: Producers' sets of offerings to the day-ahead pool market

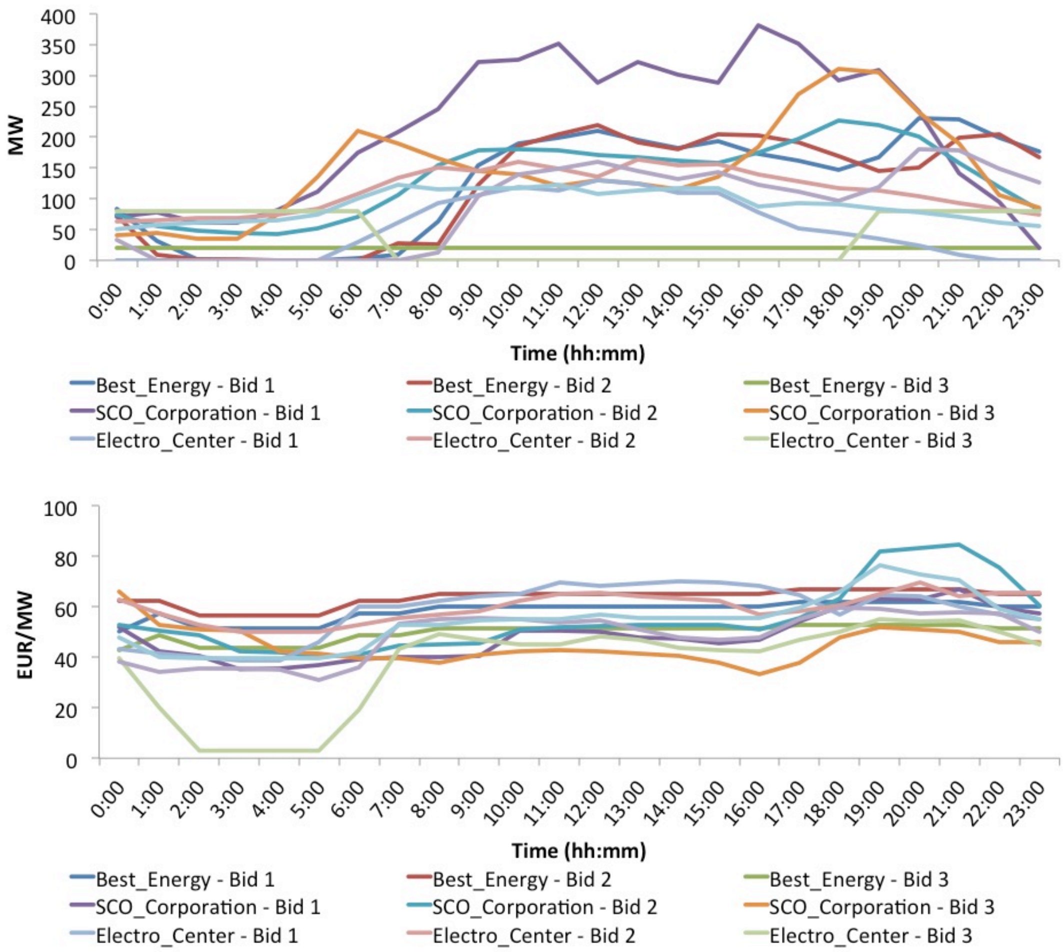

Figure 5.3: Retailers' purchase bids to the market (power and price)

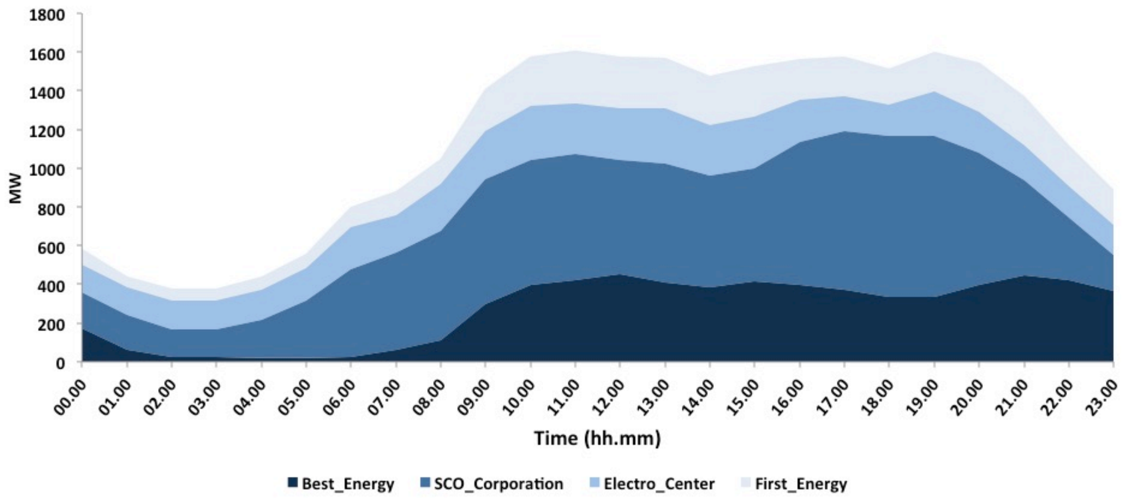

Figure 5.4: Retailers' power bids shares on the market

Figure 5.4 shows how the considered hypothetical demand is shared among retail companies. Firstly, for each model, a first day-ahead pool market simulation was run with the standard players and the respective producer $P0_n$. This demand-supply matching process of electricity volumes, which characterises the pool market clearing operation, occurs as mentioned previously in Section 2.3, yielding twenty-four hourly transacted energy volumes and market marginal prices, determining which purchase and sale bids were accepted and those which were not.

Then, a profit optimisation session was simulated using the market marginal prices values as GenCo's — $P1_{\{T,T\&W,H\&W\}}$ — market prices forecasts (Equation 5.1). Therefore, in this case the variable agent's bid was not manually submitted to the market operator but computed by the self-scheduling model under analysis, optimising the commitment and production of its portfolio according to an input of prices forecasts.

$$\pi_{Pool_t} = V_{1,t}, \forall t = \{1, 2, ..., 24\}. \tag{5.1}$$

This testing method is based on comparing both produced energy volumes and clearing-market prices from the first pool market simulation and the output of the considered optimisation models that will define the offerings to market in the second market session. By comparing the first market clearance and the further self-scheduling data, based on the market prices given by the MMP from the first iteration, this exercise allows to see whether the behaviour of the models demonstrates the desired sensitivity to prices forecasts in order to properly schedule the commitment and output of a GenCo's generation units portfolio. In case the transacted volumes during the first market simulation are similar to the ones yielded from the model, the conclusion that an important part of the optimisation algorithm is working properly can be drawn. Table 5.1, Table 5.2 and Table 5.3 show data from the three different validation exercises.

For each model (and Table), it can be seen that the volumes "in merit" from the first market session of the P_n producers are coincident with those from the self-scheduling optimisation which had the MMP from the first session as forecast input. Accordingly, one can say that, by using a self-scheduling optimisation model, a generation company would be able to estimate better its most probable minimum revenue, and to prepare its actions according to the circumstances. By foreseeing the failure of some units to be "in merit", the producer can then be aware of the low probability of having to start them in order to supply the market and fulfil the demand. Additionally, as expected, hourly market marginal prices were a (perfect) match when comparing both market sessions.

Despite coherence of output data, some discrepancies can be easily spotted on Table 5.1, regarding the testing of the "*Thermal Portfolio*" "*Hydro and Wind Portfolio*" and model (see also Figure 5.5). Due to the fact that the agent's producing unit was the last "in merit" unit to be accepted by the market operator, and thus is the marginal unit, only part of the sale bid was effectively transacted via-pool. This event is patent at 01:00h, first, and then at 05:00h and 06:00h. The major motive for this to happen is the input data necessary for the model to optimise generation: because this is a profit-driven optimisation, a given GenCo's generation is defined on price forecasts and not on demand forecasts, making the model insensitive to the demand-side necessity (or not) of certain volumes of electricity. Accordingly, one can assume that a volume-driven optimisation, by opposition to a price-driven optimisation, would prevent this situation.

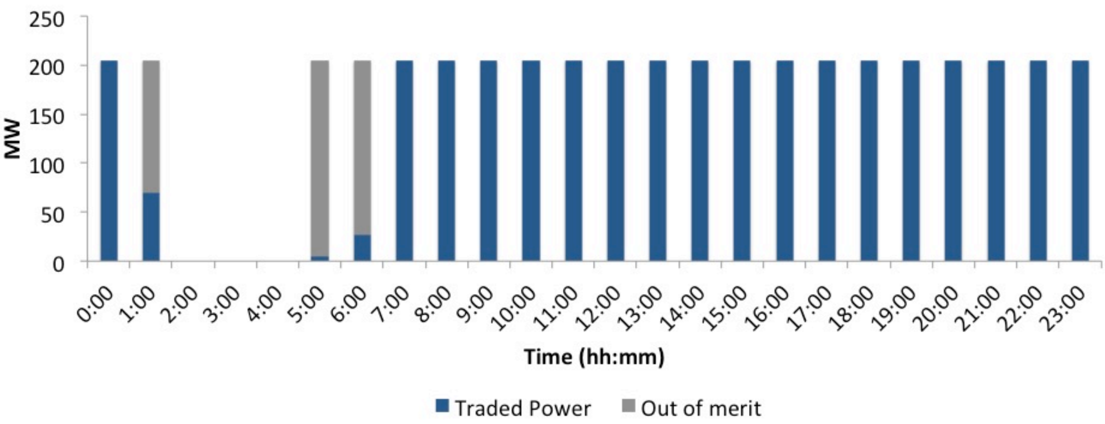

Figure 5.5: Partial acceptance of the thermal producer's ($P1_T$) bided electricity volumes

Time	Manual Initial Bid ($P0_T$)		Market Session 1		Self-Scheduling Bid ($P1_T$)		Market Session 2	
	Power	**Marginal Cost**	**Power**	**MMP**	**Power**	**Marginal Cost**	**Power**	**MMP**
h	MW	€/MWh	MW	€/MWh	MW	€/MWh	MW	€/MWh
00:00	205,00	41,20	205,00	41,40	205,00	41,20	205,00	41,40
01:00	205,00	41,20	69,89	41,20	205,00	41,20	69,89	41,20
02:00	205,00	41,20	0,00	41,00	0,00	41,20	0,00	41,00
03:00	205,00	41,20	0,00	41,00	0,00	41,20	0,00	41,00
04:00	205,00	41,20	0,00	41,00	0,00	41,20	0,00	41,00
05:00	205,00	41,20	5,02	41,20	205,00	41,20	5,02	41,20
06:00	205,00	41,20	27,60	41,20	205,00	41,20	27,60	41,20
07:00	205,00	41,20	205,00	41,40	205,00	41,20	205,00	41,40
08:00	205,00	41,20	205,00	41,40	205,00	41,20	205,00	41,40
09:00	205,00	41,20	205,00	54,50	205,00	41,20	205,00	54,50
10:00	205,00	41,20	205,00	55,22	205,00	41,20	205,00	55,22
11:00	205,00	41,20	205,00	41,40	205,00	41,20	205,00	41,40
12:00	205,00	41,20	205,00	41,40	205,00	41,20	205,00	41,40
13:00	205,00	41,20	205,00	41,40	205,00	41,20	205,00	41,40
14:00	205,00	41,20	205,00	53,00	205,00	41,20	205,00	53,00
15:00	205,00	41,20	205,00	41,40	205,00	41,20	205,00	41,40
16:00	205,00	41,20	205,00	53,00	205,00	41,20	205,00	53,00
17:00	205,00	41,20	205,00	53,00	205,00	41,20	205,00	53,00
18:00	205,00	41,20	205,00	53,00	205,00	41,20	205,00	53,00
19:00	205,00	41,20	205,00	53,00	205,00	41,20	205,00	53,00
20:00	205,00	41,20	205,00	53,00	205,00	41,20	205,00	53,00
21:00	205,00	41,20	205,00	62,00	205,00	41,20	205,00	62,00
22:00	205,00	41,20	205,00	53,00	205,00	41,20	205,00	53,00
23:00	205,00	41,20	205,00	53,00	205,00	41,20	205,00	53,00

Table 5.1: "*Thermal Portfolio*" model validation results

Time	Manual Initial Bid ($P0_T\&W$)		Market Session 1		Self-Scheduling Bid ($P1_T\&W$)		Market Session 2	
	Power	**Marginal Cost**	**Power**	**MMP**	**Power**	**Marginal Cost**	**Power**	**MMP**
h	MW	€$/MWh$	MW	€$/MWh$	MW	€$/MWh$	MW	€$/MWh$
00:00	110,00	44,20	110,00	45,00	110,00	44,20	110,00	45,00
01:00	110,00	44,20	0,00	41,00	0,00	44,20	0,00	41,00
02:00	110,00	44,20	0,00	41,00	0,00	44,20	0,00	41,00
03:00	110,00	44,20	0,00	41,00	0,00	44,20	0,00	41,00
04:00	110,00	44,20	0,00	41,00	0,00	44,20	0,00	41,00
05:00	110,00	44,20	0,00	39,00	0,00	44,20	0,00	39,00
06:00	110,00	44,20	0,00	41,40	0,00	44,20	0,00	41,40
07:00	110,00	44,20	110,00	44,65	110,00	44,20	110,00	44,65
08:00	110,00	44,20	110,00	53,00	110,00	44,20	110,00	53,00
09:00	110,00	44,20	110,00	53,00	110,00	44,20	110,00	53,00
10:00	110,00	44,20	110,00	53,00	110,00	44,20	110,00	53,00
11:00	110,00	44,20	110,00	53,00	110,00	44,20	110,00	53,00
12:00	110,00	44,20	110,00	53,00	110,00	44,20	110,00	53,00
13:00	110,00	44,20	110,00	53,00	110,00	44,20	110,00	53,00
14:00	110,00	44,20	110,00	45,00	110,00	44,20	110,00	45,00
15:00	110,00	44,20	110,00	53,00	110,00	44,20	110,00	53,00
16:00	110,00	44,20	110,00	45,00	110,00	44,20	110,00	45,00
17:00	110,00	44,20	110,00	53,00	110,00	44,20	110,00	53,00
18:00	110,00	44,20	110,00	61,00	110,00	44,20	110,00	61,00
19:00	110,00	44,20	110,00	63,24	110,00	44,20	110,00	63,24
20:00	110,00	44,20	110,00	55,00	110,00	44,20	110,00	55,00
21:00	110,00	44,20	110,00	64,09	110,00	44,20	110,00	64,09
22:00	110,00	44,20	110,00	44,20	110,00	44,20	110,00	44,20
23:00	110,00	44,20	110,00	53,00	110,00	44,20	110,00	53,00

Table 5.2: "*Thermal and Wind Portfolio*" model validation results

Time	**Manual Initial Bid ($P0_H\&W$)**		**Market Session 1**		**Self-Scheduling Bid ($P1_H\&W$)**		**Market Session 2**	
	Power	**Marginal Cost**	**Power**	**MMP**	**Power**	**Marginal Cost**	**Power**	**MMP**
h	MW	€/MWh	MW	€/MWh	MW	€/MWh	MW	€/MWh
00:00	115,87	41,00	115,87	45,00	115,87	41,00	115,87	45.00
01:00	115,87	41,00	115,87	41,31	115,87	41,00	115,87	41,31
02:00	115,87	41,00	115,87	41,00	115,87	41,00	115,87	41,00
03:00	115,87	41,00	107,13	41,00	115,87	41,00	107,13	41,00
04:00	115,87	41,00	115,87	41,00	115,87	41,00	115,87	41,00
05:00	115,87	41,00	115,87	41,00	115,87	41,00	115,87	41,00
06:00	115,87	41,00	115,87	41,11	115,87	41,00	115,87	41,11
07:00	115,87	41,00	115,87	44,65	115,87	41,00	115,87	44,65
08:00	115,87	41,00	115,87	51,29	115,87	41,00	115,87	51,29
09:00	115,87	41,00	115,87	53,00	115,87	41,00	115,87	53,00
10:00	115,87	41,00	115,87	53,00	115,87	41,00	115,87	53,00
11:00	115,87	41,00	115,87	53,00	115,87	41,00	115,87	53,00
12:00	115,87	41,00	115,87	53,00	115,87	41,00	115,87	53,00
13:00	115,87	41,00	115,87	53,00	115,87	41,00	115,87	53,00
14:00	115,87	41,00	115,87	45,00	115,87	41,00	115,87	45,00
15:00	115,87	41,00	115,87	53,00	115,87	41,00	115,87	53,00
16:00	115,87	41,00	115,87	45,00	115,87	41,00	115,87	45,00
17:00	115,87	41,00	115,87	53,00	115,87	41,00	115,87	53,00
18:00	115,87	41,00	115,87	61,00	115,87	41,00	115,87	61,00
19:00	115,87	41,00	115,87	63,24	115,87	41,00	115,87	63,24
20:00	115,87	41,00	115,87	55,00	115,87	41,00	115,87	55,00
21:00	115,87	41,00	115,87	64,09	115,87	41,00	115,87	64,09
22:00	115,87	41,00	115,87	41,40	115,87	41,00	115,87	41,40
23:00	115,87	41,00	115,87	53,00	115,87	41,00	115,87	53,00

Table 5.3: "*Hydro and Wind Portfolio*" model validation results

5.2 Case Study II: Effect of High Levels of Renewable Variable Generation on Pool Market Prices

Aiming to illustrate the functionalities of the MAN-REM through the demonstration of the effect of different non-dispatchable electricity generation levels on pool market marginal prices, two day-ahead pool market sessions were simulated. This matter assumes capital importance at a time when clean energy generation systems, such as wind and photovoltaics, are under profound deployment worldwide.

Regarding the retail market players, a set of bids comprised of prices and energy volumes, similar to the one considered in Section 5.1 for the first case study (Figure 5.3), was used (Tables B.1 – B.4). On the other hand, several production units operating according various generation technologies were allocated to the four GenCos, who played an active role in this market simulation: *GenCo 1*, *GenCo 2*, *GenCo 3* and *GenCo 4* (Table 5.4).

Two market simulations were carried out in order to illustrate the influence of a scenario characterised by high wind speed against a scenario of low wind speed, namely by comparing their hourly marginal prices. Hence, the main difference between the two simulations is precisely the input data (to the self-scheduling optimisation models) related to the wind speed forecasts, which will allow the producer to estimate the hourly wind production for the next twenty-four hours and hence its whole portfolio commitment. Table C.1 shows in detail the hourly wind speed forecasts used in this case for both the low and high speed scenarios. Likewise, Table C.2 shows the actual output wind power generation from the considered wind farms computed, for each case, according to the technical characteristics of the installed wind turbines' models (see Table A.1).

As mentioned above, a set of generation companies owning, each of them, several generation units, was considered. Tables C.3 – C.9 describe the technical specificities of each of these plants. Figure 5.6 shows the composition of the group of electricity producers that constitutes the electricity generation system considered, according to the generation technology of their power plants. Consequently, an overall generation capacity of $2\ 831,65$ MW constitutes the electrical system here simulated, having considerable contributions from hydro power, coal, an important share of wind power, and smaller power availability from natural gas and oil.

Generation Company	**Thermal**	**Hydro**	**Wind**
GenCo 1	*Thermal 1* *Thermal 2* *Thermal 3*	-	-
GenCo 2	-	*Hydro 2* *Hydro 3*	*W1* *W2*
GenCo 3	*Thermal 4* *Thermal 5*	-	*W3* *W4* *W5*
GenCo 4	*Thermal 6*	*Hydro 6*	*W6* *W7*

Table 5.4: GenCos' portfolios composition

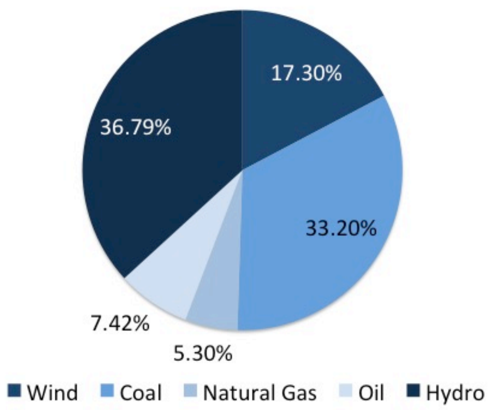

Figure 5.6: Representativity of each generation technology composing the generation system

The generation costs considered for hydro [61, 62] and thermal power [58, 59] plants follow state-of-art fixed and variable costs, whereas marginal costs of wind power were considered to be in the interval referred in Section 2.4. Marginal costs of all the units that participate in the market are shown in Table C.9. Despite other costs are shown in Table C.9, and because producers are expected to bid in the market at marginal costs, this case study considered only the costs on the last column (€/MWh).

Figure 5.7 depicts the market marginal prices (see Table C.10 for further details) yielded from the two pool market simulations. A considerable decay of market marginal prices can be easily noticed when higher wind speeds are registered due to their influence on wind farms' output production and, consequently, to the flooding of the pool market with wind power at lower (if not null) marginal costs.

As already discussed in Section 2.4, wind power's low OPEX costs easily result in lower market marginal costs because of its effect on pushing more expensive generation units onwards and, oftentimes, disposing them from the group of the *in merit* producers. For the present exercise, an average market marginal price reduction of around 4,43€/MWh was registered, having the price spreads oscillated from a minimum of 0,00 €/MWh — at 06:00h and 21:00h — to a maximum of 17,65 €/MWh — registered at 00:00h.

By examining Figures 5.8 and 5.9 one can get to the conclusion that marginal prices fall is intrinsically linked to the avoidance of calling fuel-fired power plants to produce electricity through the use of electrical energy generated by wind farms. Specifically, during the night period, namely between 00:00h and 05:00h, the reduction of reliance on coal can clearly be noticed when a high output wind production is registered during these hours of low load.

Besides the market marginal price reduction, another effect of high shares of electricity production from wind farms on the market clearance was verified. In fact, the transacted volume of energy through this pool platform increased when higher wind generation was registered. Whereas in a low wind speed scenario (and thus low wind output production), the overall volume of negotiated energy was of about 17 083,23 MWh, under a high wind speed scenario, the daily amount of traded electricity via-pool rose from approximately 2 799,29 MWh up to 19 882,52 MWh. This non-surprising event is justified by the increase of the social welfare and the increase of quantity demanders can pay for.

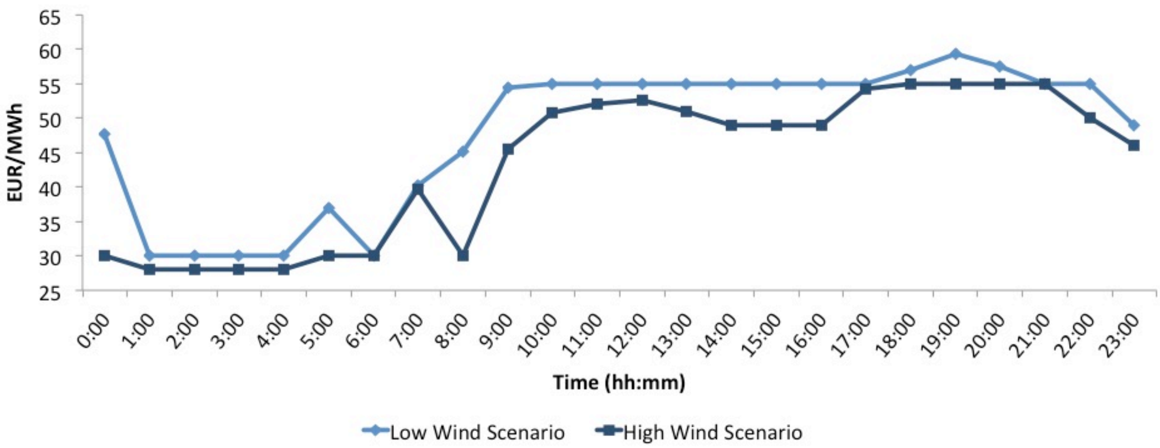

Figure 5.7: Day-ahead pool market clearing prices

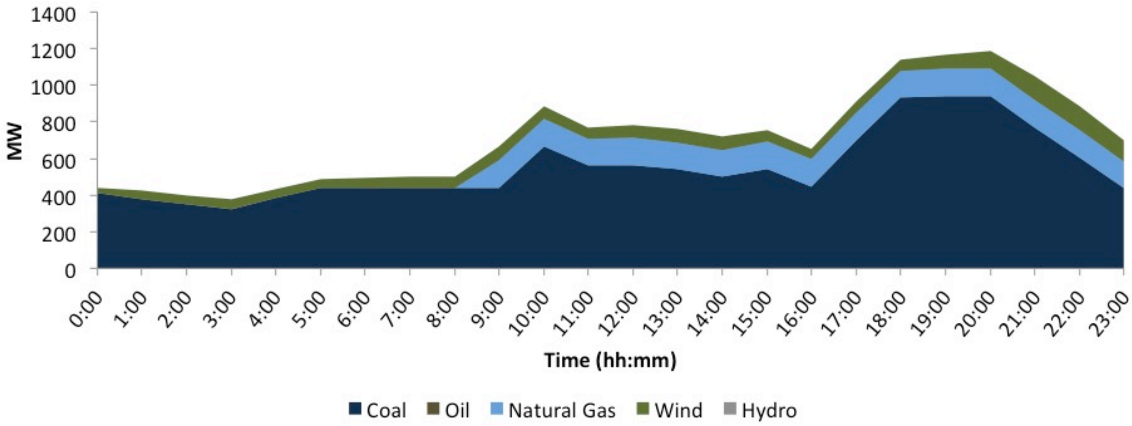

Figure 5.8: Hourly power generation by technology under a low wind speed scenario

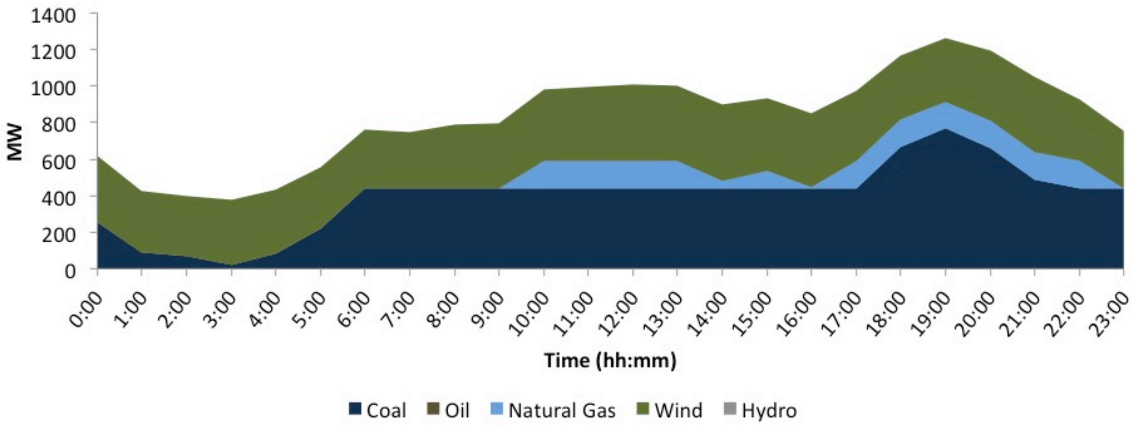

Figure 5.9: Hourly power generation by technology under a high wind speed scenario

It should also be highlighted the fact that, in both market scenarios, neither hydro nor oil generation technologies managed to be “in merit” in the simulated markets due to their higher marginal costs when compared to the remaining sources of power production.

Conclusions and Further Developments

In an era of great demographic expansion and relative levelling of living standards in some of the more densely populated areas of the planet, the human kind is facing extreme challenges to provide to more than seven billion people the goods and services that, not so far from us, were only part of a minority's life. Electricity, as almost any other utility, has seen its demand rocket over the last hundred years and even more with the industrial and economic explosion of countries, such as India, China, Russia and others emerging regions. Massive quantities of demanded electrical energy have evidenced even more a chronicle problem of this sector: a profound reliance on fossil fuels burning to fire power plants and its inherent greenhouse effect gases emissions with all the negative aspects of their spread into the atmosphere. Currently, some previous policies regarding the sustainability of our society, including of the energy sector, are already yielding some changes on the electricity generation landscape, with the introduction of considerable renewable and CO_2-free production technologies, including wind, solar and geothermal, as well as pumping and chemical storage systems, which promote wiser and more efficient use of the electricity produced.

The current diversity of production technologies with distinct operation regimes, costs and maturities has provoked the rise of market competition up to levels never seen before, exposing particularly generation companies to higher financial and operational risks that need to be forearmed for the sake of an efficient sector. Market simulators, particularly multi-agent systems with higher adherence to the reality of market and negotiation environments, are (extraordinary) tools that allow the study of the interactions between agents from different backgrounds and with distinct expectations, as well as the consequences of the introduction of new types of agents, generation technologies, market regulations or any other aspects.

Hereupon, the aim of this work was to provide the already existent MAN-REM market simulator with a set of tools that could be helpful to a producer to self-schedule its units' commitment and output production based on technical specificities of the generation portfolio, market prices and renewable production forecasts, in order to maximise its financial profit within a considered period span.

After the conclusion of the simulator's expansion, three self-scheduling models had been added to the software, each of them with special focus on a particular generation portfolio's technology composition. Hence, producers owning thermal units, thermal and wind units and hydro and wind units were considered and are now allowed to self-schedule their production towards a profitable sale of the output electricity through both bilateral contracts and pool market. Interface windows to enable an easy and efficient addition of agents and portfolios to the market were also patched to the existent version of MAN-REM as well as an electronic trading mechanism for bilateral transactions.

The case study adopted to demonstrate the optimisation algorithms has demonstrated that a good coordination between the input prices forecasts and the output generation and commitment of units exists. Units whose marginal prices are above the forecasted prices the producers expect to sell their energy by, are immediately excluded from the generation planning in order to avoid financial losses.

Also, by developing a second case study, the software has allowed to demonstrate that renewable generation units, with traditionally lower marginal costs, surpass more marginally expensive production technologies such as thermal or hydro. This substitution of technologies on the meritocratic hierarchy results on the displacement of coal- and gas-fired power plants with beneficial consequences whether for the reduction of GHG emissions or for the lowering of pool market prices. In fact, weak demand periods, usually during the night, are some time characterised by substantial reductions of the market clearing prices, when sometimes the energy is transacted freely or, depending on the region, at negative prices.

6.1 Further Developments

Regarding future work, and aiming to improve the MAN-REM multi-agent simulator and some of the added features, resulting from this dissertation, a few suggestions may be followed and used to make it a more robust and realistic tool. The following development paths are then proposed:

- Proceed with further testings in order to prove the logical stability and coherence of the self-scheduling optimisation models added to the MAN-REM, assuring a correct unit commitment status and output production;

- Complement the self-scheduling optimisation tools, added as result of this work, with the introduction of a certain level of uncertainty, which characterises a real market situation, for instance on the day-ahead market prices forecasts, and the uncertainty arising from imperfect wind speed and hydro inflows forecasts. Risk assessment and management tools should then be considered as the next step to turn market simulations more realistic;

- Development of new self-scheduling optimisation models focused on broader units portfolio compositions, such as photovoltaic power, hydro storage and even chemical battery storage facilities, providing the user with the chance to have more realistic simulations by adding, to his portfolio, technologies that are already widely used Worldwide;
- Study, development and implementation of a more realistic market system where day-ahead pool market clearance is operated simultaneously with bilateral negotiation and agreements in order to assure that a correct settlement of all energy volumes, bought and produced, is properly achieved.

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Appendices

Wind Power Turbine Models

Model	**E33**	**E44**	**E48**	**E53**	**E70**	**E82E2**	**E82E2i**	**E82E3**	**E101**	**E126**
Power *(MW)*	0,33	0,90	0,80	0,80	2,30	2,00	2,30	3,00	3,00	7,50
Rotor Diam. *(m)*	33,4	44,0	48,0	52,9	71,0	82,0	82,0	82,0	101,0	127,0
Cut-in Speed *(m/s)*	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
Cut-out Speed *(m/s)*	26,0	26,0	26,0	26,0	26,0	26,0	26,0	26,0	26,0	26,0
Wind *(m/s)*	**Power Coefficient**									
[**0-1**[	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
[**1-2**[	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
[**2-3**[	0,000	0,000	0,000	0,190	0,100	0,120	0,120	0,120	0,076	0,000
[**3-4**[	0,350	0,160	0,170	0,390	0,270	0,290	0,290	0,290	0,279	0,263
[**4-5**[	0,400	0,340	0,350	0,440	0,360	0,400	0,400	0,400	0,376	0,352
[**5-6**[	0,450	0,430	0,430	0,460	0,420	0,430	0,430	0,430	0,421	0,423
[**6-7**[	0,470	0,480	0,460	0,480	0,460	0,460	0,460	0,460	0,452	0,453
[**7-8**[	0,500	0,490	0,470	0,490	0,480	0,480	0,480	0,480	0,469	0,470
[**8-9**[	0,500	0,500	0,480	0,490	0,500	0,490	0,490	0,490	0,478	0,478
[**9-10**[	0,500	0,500	0,500	0,490	0,500	0,500	0,500	0,500	0,478	0,477
[**10-11**[	0,470	0,500	0,500	0,480	0,500	0,490	0,490	0,490	0,477	0,483
[**11-12**[	0,410	0,480	0,450	0,420	0,490	0,420	0,440	0,440	0,439	0,470
[**12-13**[	0,350	0,440	0,390	0,340	0,450	0,350	0,380	0,390	0,358	0,429
[**13-14**[	0,280	0,390	0,320	0,270	0,390	0,290	0,320	0,350	0,283	0,381
[**14-15**[	0,230	0,330	0,270	0,220	0,340	0,230	0,260	0,300	0,227	0,329
[**15-16**[	0,180	0,280	0,220	0,180	0,280	0,190	0,220	0,260	0,184	0,281
[**16-17**[	0,150	0,240	0,180	0,150	0,230	0,150	0,180	0,220	0,152	0,236
[**17-18**[	0,130	0,200	0,150	0,120	0,190	0,130	0,150	0,190	0,127	0,199
[**18-19**[	0,110	0,170	0,130	0,100	0,160	0,110	0,120	0,160	0,107	0,168
[**19-20**[	0,090	0,140	0,110	0,090	0,140	0,090	0,110	0,140	0,091	0,142
[**20-21**[	0,080	0,120	0,090	0,080	0,120	0,080	0,090	0,120	0,078	0,122
[**21-22**[	0,070	0,110	0,080	0,060	0,100	0,070	0,080	0,100	0,067	0,105
[**22-23**[	0,060	0,090	0,070	0,060	0,090	0,060	0,070	0,090	0,058	0,092
[**23-24**[	0,050	0,080	0,060	0,050	0,080	0,050	0,060	0,080	0,051	0,080
[**24-25**[	0,050	0,070	0,050	0,040	0,070	0,050	0,050	0,070	0,045	0,071
[**25-26**[	0,040	0,060	0,050	0,040	0,060	0,040	0,050	0,060	0,040	0,063

Table A.1: Wind power turbine models

Case Study I

	Best Energy					
	Bid 1		**Bid 2**		**Bid 3**	
Time h	Power MW	Price €$/MW$	Power MW	Price €$/MW$	Power MW	Price €$/MW$
00:00	82,80	50,27	72,44	62,27	20,00	42,72
01:00	32,11	57,27	8,44	62,27	20,00	48,68
02:00	0,91	51,59	2,18	56,59	20,00	43,86
03:00	0,00	51,59	2,18	56,59	20,00	43,86
04:00	0,00	51,59	0,00	56,59	20,00	43,86
05:00	0,00	51,59	0,00	56,59	20,00	43,86
06:00	2,72	57,27	0,00	62,27	20,00	48,68
07:00	9,85	57,27	28,63	62,27	20,00	48,68
08:00	62,93	60,34	25,45	65,33	20,00	51,29
09:00	153,49	60,34	121,91	65,33	20,00	51,29
10:00	190,05	60,34	186,36	65,33	20,00	51,29
11:00	199,39	60,34	204,63	65,33	20,00	51,29
12:00	210,66	60,34	219,63	65,33	20,00	51,29
13:00	194,92	60,34	191,72	65,33	20,00	51,29
14:00	182,27	60,34	181,27	65,33	20,00	51,29
15:00	193,25	60,34	205,17	65,33	20,00	51,29
16:00	172,97	60,34	203,17	65,33	20,00	51,29
17:00	161,02	62,00	192,44	67,01	20,00	52,70
18:00	147,36	62,00	168,55	67,01	20,00	52,70
19:00	168,27	62,00	145,91	67,01	20,00	52,70
20:00	230,07	62,00	149,72	67,01	20,00	52,70
21:00	229,46	62,00	198,55	67,01	20,00	52,70
22:00	198,88	60,34	204,17	65,33	20,00	51,29
23:00	177,02	60,34	168,27	65,33	20,00	51,29

Table B.1: Retailers' market bids — Best Energy

	SCO Corporation					
	Bid 1		Bid 2		Bid 3	
Time h	Power MW	Price $€/MW$	Power MW	Price $€/MW$	Power MW	Price $€/MW$
00:00	70,00	52,13	74,41	53,02	40,00	66,09
01:00	78,40	42,5	55,04	50,41	45,00	53,00
02:00	61,59	40,50	48,58	48,54	35,00	51,13
03:00	61,59	35,29	45,34	42,49	35,00	50,79
04:00	82,59	35,40	42,11	42,06	75,00	42,50
05:00	112,00	36,97	51,81	40,29	135,00	41,29
06:00	175,00	39,34	71,19	41,11	210,00	39,61
07:00	208,60	40,15	106,72	44,65	190,00	39,63
08:00	246,39	40,06	155,16	45,13	165,00	38,02
09:00	322,00	40,70	177,77	45,50	145,00	40,88
10:00	326,20	50,41	181,00	50,81	140,00	42,52
11:00	351,39	50,41	177,77	52,06	120,00	42,79
12:00	288,39	50,09	171,32	52,54	130,00	42,40
13:00	322,00	48,00	168,08	53,02	125,00	41,65
14:00	301,00	47,25	161,63	53,02	115,00	40,74
15:00	193,25	60,34	205,17	65,33	20,00	51,29
16:00	380,79	46,95	174,55	50,81	185,00	33,31
17:00	351,39	54,22	197,16	55,38	270,00	38,02
18:00	292,60	60,02	226,22	63,25	310,00	48,00
19:00	309,39	63,24	219,77	82,00	305,00	52,04
20:00	242,19	62,68	200,38	83,15	240,00	51,13
21:00	141,39	66,76	158,39	84,70	190,00	50,13
22:00	95,19	59,84	119,63	75,50	105,00	46,00
23:00	19,60	57,43	80,87	60,54	85,00	46,00

Table B.2: Retailers' market bids — SCO Corporation

	Electro Center					
	Bid 1		**Bid 2**		**Bid 3**	
Time h	Power MW	Price €$/MW$	Power MW	Price €$/MW$	Power MW	Price €$/MW$
00:00	0,00	43,18	62,70	62,88	80,18	39,49
01:00	0,00	41,31	64,90	57,31	80,18	20,00
02:00	0,00	40,00	68,26	53,02	80,18	3,00
03:00	0,00	38,56	68,79	50,15	80,18	3,00
04:00	0,00	38,65	73,37	50,06	80,18	3,00
05:00	0,00	46,16	84,02	50,06	80,18	3,00
06:00	30,46	60,29	107,66	53,02	80,18	19,12
07:00	61,43	60,34	134,77	55,68	0,00	43,50
08:00	92,65	62,63	150,10	56,93	0,00	49,00
09:00	105,87	64,11	145,42	58,34	0,00	47,00
10:00	118,62	65,11	159,97	62,45	0,00	45,00
11:00	113,65	69,90	148,83	65,06	0,00	45,00
12:00	130,38	68,40	136,33	65,37	0,00	48,38
13:00	124,37	69,30	163,52	64,19	0,00	46,88
14:00	109,25	70,00	153,66	63,41	0,00	43,65
15:00	109,86	69,90	155,53	62,54	0,00	43,04
16:00	77,43	68,30	138,66	56,93	0,00	42,50
17:00	51,72	64,69	128,52	58,34	0,00	47,00
18:00	45,36	57,00	117,66	60,68	0,00	50,11
19:00	34,93	64,69	113,33	65,13	80,18	55,00
20:00	23,53	64,11	103,62	69,75	80,18	54,00
21:00	9,77	60,34	92,25	64,09	80,18	54,70
22:00	0,00	56,93	83,05	65,62	80,18	50,11
23:00	0,00	55,22	74,52	65,69	80,18	45,13

Table B.3: Retailers' market bids — Electro Center

	First Energy			
	Bid 1		**Bid 2**	
Time *h*	Power *MW*	Price €/*MW*	Power *MW*	Price €/*MW*
00:00	32,81	38,13	50,65	47,65
01:00	0,00	34,06	57,75	40,00
02:00	0,00	35,40	61,36	39,66
03:00	0,00	35,40	62,49	39,66
04:00	0,00	35,20	65,80	39,65
05:00	0,00	31,00	73,69	39,66
06:00	0,00	36,04	100,76	41,88
07:00	0,00	53,13	122,01	52,95
08:00	12,93	55,20	115,18	53,02
09:00	103,48	55,38	116,36	54,50
10:00	140,05	55,00	116,58	55,22
11:00	149,39	53,72	123,37	55,22
12:00	160,66	54,81	108,61	56,93
13:00	144,92	51,00	113,94	55,49
14:00	132,27	48,00	117,69	55,49
15:00	143,25	47,00	118,02	55,38
16:00	122,97	48,00	87,20	55,38
17:00	111,01	55,22	92,69	59,68
18:00	97,37	59,68	91,37	66,12
19:00	118,27	59,38	83,51	76,34
20:00	180,07	57,50	77,91	73,06
21:00	179,46	57,70	71,00	70,58
22:00	148,88	57,61	61,93	59,43
23:00	127,02	50,20	56,47	55,20

Table B.4: Retailers' market bids — First Energy

	P0					
	Thermal Portfolio Model		Hydro+Wind Portfolio Model		Thermal + Wind Portfolio Model	
Time h	Power MW	Price €/MW	Power MW	Price €/MW	Power MW	Price €/MW
00.00	205,00	41,20	115,87	41,00	110,00	44,20
01.00	205,00	41,20	115,87	41,00	110,00	44,20
02.00	205,00	41,20	115,87	41,00	110,00	44,20
03.00	205,00	41,20	115,87	41,00	110,00	44,20
04.00	205,00	41,20	115,87	41,00	110,00	44,20
05.00	205,00	41,20	115,87	41,00	110,00	44,20
06.00	205,00	41,20	115,87	41,00	110,00	44,20
07.00	205,00	41,20	115,87	41,00	110,00	44,20
08.00	205,00	41,20	115,87	41,00	110,00	44,20
09.00	205,00	41,20	115,87	41,00	110,00	44,20
10.00	205,00	41,20	115,87	41,00	110,00	44,20
11.00	205,00	41,20	115,87	41,00	110,00	44,20
12.00	205,00	41,20	115,87	41,00	110,00	44,20
13.00	205,00	41,20	115,87	41,00	110,00	44,20
14.00	205,00	41,20	115,87	41,00	110,00	44,20
15.00	205,00	41,20	115,87	41,00	110,00	44,20
16.00	205,00	41,20	115,87	41,00	110,00	44,20
17.00	205,00	41,20	115,87	41,00	110,00	44,20
18.00	205,00	41,20	115,87	41,00	110,00	44,20
19.00	205,00	41,20	115,87	41,00	110,00	44,20
20.00	205,00	41,20	115,87	41,00	110,00	44,20
21.00	205,00	41,20	115,87	41,00	110,00	44,20
22.00	205,00	41,20	115,87	41,00	110,00	44,20
23.00	205,00	41,20	115,87	41,00	110,00	44,20

Table B.5: Producers' market bids — P0

	P2							
	Bid 1		**Bid 2**		**Bid 3**		**Bid 4**	
Time h	Power MW	Price €$/MW$	Power MW	Price €$/MW$	Power MW	Price €$/MW$	Power MW	Price €$/MW$
00.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
01.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
02.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
03.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
04.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
05.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
06.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
07.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
08.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
09.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
10.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
11.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
12.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
13.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
14.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
15.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
16.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
17.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
18.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
19.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
20.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
21.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
22.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00
23.00	120,00	41,00	85,00	53,00	90,00	61,00	40,00	70,00

Table B.6: Producer's day-ahead market bids — P2

	P3							
	Bid 1		Bid 2		Bid 3		Bid 4	
Time h	Power MW	Price $€/MW$	Power MW	Price $€/MW$	Power MW	Price $€/MW$	Power MW	Price $€/MW$
00.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
01.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
02.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
03.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
04.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
05.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
06.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
07.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
08.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
09.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
10.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
11.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
12.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
13.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
14.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
15.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
16.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
17.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
18.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
19.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
20.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
21.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
22.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00
23.00	47,00	45,00	84,00	32,00	65,00	41,40	50,00	68,00

Table B.7: Producer's day-ahead market bids — P3

	P4					
	Bid 1		**Bid 2**		**Bid 3**	
Time h	Power MW	Price $€/MW$	Power MW	Price $€/MW$	Power MW	Price $€/MW$
00.00	30,00	39,00	20,00	55,00	0,00	80,00
01.00	30,00	39,00	20,00	55,00	0,00	80,00
02.00	30,00	39,00	20,00	55,00	0,00	80,00
03.00	30,00	39,00	20,00	55,00	0,00	80,00
04.00	30,00	39,00	20,00	55,00	0,00	80,00
05.00	30,00	39,00	20,00	55,00	0,00	80,00
06.00	30,00	39,00	20,00	55,00	0,00	80,00
07.00	30,00	39,00	20,00	55,00	0,00	80,00
08.00	30,00	39,00	20,00	55,00	0,00	80,00
09.00	30,00	39,00	20,00	55,00	0,00	80,00
10.00	30,00	39,00	20,00	55,00	0,00	80,00
11.00	30,00	39,00	20,00	55,00	0,00	80,00
12.00	30,00	39,00	20,00	55,00	0,00	80,00
13.00	30,00	39,00	20,00	55,00	0,00	80,00
14.00	30,00	39,00	20,00	55,00	0,00	80,00
15.00	30,00	39,00	20,00	55,00	0,00	80,00
16.00	30,00	39,00	20,00	55,00	0,00	80,00
17.00	30,00	39,00	20,00	55,00	0,00	80,00
18.00	30,00	39,00	20,00	55,00	0,00	80,00
19.00	30,00	39,00	20,00	55,00	0,00	80,00
20.00	30,00	39,00	20,00	55,00	0,00	80,00
21.00	30,00	39,00	20,00	55,00	0,00	80,00
22.00	30,00	39,00	20,00	55,00	0,00	80,00
23.00	30,00	39,00	20,00	55,00	0,00	80,00

Table B.8: Producer's day-ahead market bids — P4

Case Study II

Time	Low Wind Speed Scenario							High Wind Speed Scenario						
	GenCo 2		GenCo 3			GenCo 4		GenCo 2		GenCo 3			GenCo 4	
	W1	W2	W3	W4	W5	W6	W7	W1	W2	W3	W4	W5	W6	W7
h	m/s							m/s						
00:00	3,1733	1,1861	3,6104	1,5018	2,1008	10,1033	4,6130	13,8783	11,3083	17,1775	19,5066	20,1775	10,1033	4,6130
01:00	1,4316	3,9837	3,8202	0,9715	2,6557	11,3550	2,8304	15,5816	12,5875	9,1341	15,3458	9,1341	11,3550	2,8304
02:00	3,5450	2,4275	2,6270	0,9715	3,7036	11,0733	4,0093	15,1475	13,7225	8,8466	16,3600	8,8466	11,0733	4,0093
03:00	4,6024	1,3300	1,6935	0,9715	3,5732	12,5041	3,9773	15,1475	13,2850	10,2758	12,9641	10,2758	12,5041	3,9773
04:00	2,3704	1,5890	2,9227	0,9715	2,1832	13,4991	5,3752	15,1475	14,0666	11,7491	8,8716	11,7491	13,4991	5,3752
05:00	2,6137	1,5890	2,6621	0,4412	2,0956	15,3925	6,5811	15,1475	12,9400	11,4816	7,0260	11,4816	15,3925	6,5811
06:00	2,8735	1,5890	2,9495	1,2405	2,0956	15,8733	7,2365	15,1475	10,6441	12,4741	7,7347	12,4741	15,8733	7,2365
07:00	3,2572	1,5890	2,9495	3,2065	2,0956	15,8733	6,6931	15,1475	10,2608	11,1675	8,5675	11,1675	15,8733	6,6931
08:00	3,4331	1,8480	2,9495	4,4292	2,0080	15,8733	6,7500	15,1475	12,6008	10,6291	10,5258	10,6291	15,8733	6,7500
09:00	3,6608	2,7450	2,9495	6,0400	6,0772	15,8733	8,9325	15,1475	12,9958	9,6966	13,5366	9,6966	15,8733	8,9325
10:00	2,0339	3,4555	2,9495	5,6160	4,8120	15,8733	13,9716	20,1475	12,7250	11,2850	14,9050	11,2850	15,8733	13,9716
11:00	2,3666	2,4450	3,2368	3,9593	5,3649	16,355	16,1991	19,1475	12,8450	14,8475	19,6691	14,8475	16,3550	16,1991
12:00	4,5710	1,8770	4,0735	3,6420	5,2067	15,7558	15,3458	21,1475	13,6508	17,7200	17,9033	14,7200	15,7558	15,3458
13:00	6,6225	3,8239	4,4552	2,0022	4,7890	16,3433	13,1691	15,1475	15,6350	17,3166	18,6575	14,3166	16,3433	13,1691
14:00	5,7800	3,6375	6,2171	1,4037	2,8882	16,2400	13,5216	15,1475	15,7683	14,4575	16,9316	14,4575	16,2400	13,5216
15:00	4,6335	3,9526	5,5332	1,7559	2,4401	16,2400	13,4516	15,1475	19,7550	15,5208	11,3358	15,5208	16,2400	13,4516
16:00	2,2685	1,5409	5,0180	3,0430	2,9837	16,2400	12,8450	15,1475	16,7625	15,5208	11,7183	15,5208	16,2400	12,8450
17:00	2,0774	1,9417	4,9863	5,0965	2,7591	16,2400	12,8008	15,1475	18,2725	15,5208	10,3275	15,5208	16,2400	12,8008
18:00	2,8607	3,1776	6,2130	3,0863	4,5226	16,2400	12,0100	18,7133	12,3566	16,5833	7,6667	16,5833	16,2400	12,0100
19:00	3,1933	3,5585	6,4797	2,3619	7,0323	16,1366	12,3466	19,7550	12,4366	15,6633	7,2030	15,6633	16,1366	12,3466
20:00	4,8582	6,2968	8,3261	2,4115	6,5443	15,1975	12,1391	18,8758	15,4533	15,6633	9,8133	15,6633	15,1975	12,1391
21:00	3,7891	10,1908	8,2135	3,1036	6,7231	13,5375	13,7125	13,9891	13,7591	15,6633	11,3833	15,6633	13,5375	13,7125
22:00	2,3794	11,7633	7,9535	2,757	6,5828	9,2800	14,1416	10,9083	10,9883	14,7425	11,3125	14,7425	9,2800	14,1416
23:00	2,2679	13,2458	7,2625	2,7972	2,8593	8,4666	15,2991	11,0541	11,2883	13,5300	10,6841	13,5300	8,4666	15,2991

Table C.1: Scenarios for low and high wind speed computed from the Portuguese national wind production [38]

Time	Low Wind Scenario Production							High Wind Scenario Production						
	GenCo 2		GenCo 3			GenCo 4		GenCo 2		GenCo 3			GenCo 4	
	W1	W2	W3	W4	W5	W6	W7	W1	W2	W3	W4	W5	W6	W7
h	MW							MW						
00:00	1,14	0,00	0,97	0,00	0,05	27,89	0,00	96,29	62,68	53,95	64,51	57,50	27,89	0,00
01:00	0,00	1,52	1,14	0,00	0,12	49,02	0,00	89,27	78,90	27,04	62,81	32,68	49,02	0,00
02:00	1,60	0,00	0,15	0,00	1,26	43,13	0,00	82,01	90,79	24,07	62,52	29,70	43,13	0,00
03:00	4,84	0,00	0,00	0,00	1,13	45,99	0,00	82,01	82,37	37,74	60,86	46,43	45,99	0,00
04:00	0,20	0,00	0,20	0,00	0,07	48,59	0,00	82,01	84,44	50,65	21,67	63,88	48,59	0,00
05:00	0,27	0,00	0,15	0,00	0,05	48,70	0,00	82,01	85,72	47,27	10,34	59,63	48,70	0,00
06:00	0,34	0,00	0,21	0,00	0,05	56,13	5,21	82,01	53,72	52,34	13,78	62,34	56,13	5,21
07:00	1,24	,000	0,21	0,55	0,05	56,13	3,94	82,01	48,11	43,49	19,52	54,86	56,13	3,94
08:00	1,46	0,00	0,21	1,94	0,05	56,13	4,15	82,01	79,16	41,75	36,20	51,40	56,13	4,15
09:00	1,76	0,00	0,21	6,28	9,10	56,13	10,01	82,01	86,83	32,36	60,06	39,11	56,13	10,01
10:00	0,12	1,00	0,21	4,61	3,75	56,13	29,88	81,26	81,51	44,88	69,88	56,61	56,13	29,88
11:00	0,20	0,00	0,69	1,03	5,82	50,72	22,03	78,48	83,84	60,40	66,13	66,66	50,72	22,03
12:00	4,75	0,00	1,91	0,81	5,32	54,88	25,73	82,23	89,37	59,24	67,69	64,97	54,88	25,73
13:00	16,60	1,36	2,50	0,05	3,71	50,61	25,03	82,01	99,04	55,27	64,51	59,77	50,61	25,03
14:00	10,31	1,16	7,84	0,00	0,15	49,65	27,09	82,01	101,59	55,77	69,30	61,54	49,65	27,09
15:00	4,94	1,50	5,17	0,00	0,10	49,65	26,67	82,01	100,95	58,38	44,31	61,72	49,65	26,67
16:00	0,17	0,00	3,85	0,46	0,18	49,65	26,20	82,01	102,51	58,38	48,95	61,72	49,65	26,20
17:00	0,12	0,00	3,51	3,45	0,14	49,65	25,93	82,01	94,51	58,38	34,18	61,72	49,65	25,93
18:00	0,34	0,77	7,82	0,49	3,11	49,65	21,42	89,54	74,63	58,25	13,43	62,20	49,65	21,42
19:00	1,16	1,09	8,88	0,07	14,64	48,70	13,44	86,18	76,09	60,00	11,14	63,45	48,70	13,44
20:00	5,69	10,43	20,06	0,09	11,36	49,25	11,68	91,88	95,62	60,00	29,32	63,45	49,25	11,68
21:00	1,96	47,13	19,27	0,50	12,32	53,54	28,26	98,61	91,51	60,00	44,86	63,45	53,54	28,26
22:00	0,20	70,55	17,13	0,12	11,56	29,13	26,21	79,00	59,09	59,13	44,04	65,26	29,13	26,21
23:00	0,17	81,66	13,05	0,14	0,15	22,12	23,12	70,47	62,34	56,25	37,86	62,9	22,12	23,12

Table C.2: Output wind power generation volumes

ID	Technology	Min Power MW	Max Power MW	Ramp Up MW	Ramp Down MW	Fuel Consumption t	Fuel Consumption t/MW	Production (t-1) MW
Thermal 1	Coal	30,00	120,00	40,00	65,00	45 000,00	300,00	50,00
Thermal 2	NG	120,00	550,00	100,00	120,00	2 000,00[a]	0,21[a]	150,00
Thermal 3	Coal	80,00	210,00	80,00	110,00	90 000,00	140,00	130,00
Thermal 4	Coal	20,00	110,00	30,00	50,00	50 000,00	250,00	100,00
Thermal 5	Oil	45,00	210,00	55,00	62,00	1 248,00	334,00	80,00
Thermal 6	Coal	50,00	500,00	50,00	50,00	2 430,50	55,00	0,00

(a) *Fuel Consumption* factors are in m^3 and m^3/MW for the case of natural gas units

Table C.3: Thermal power plants' general and technical specifications

Emission Factor	Coal kg/kg	Natural Gas kg/m^2	Oil kg/kg
$efco_2$	3,1604	1,84	2,8523
$efno_2$	$1,29 \cdot 10^{-3}$	$3,4 \cdot 10^{-4}$	$3,3 \cdot 10^{-4}$

Table C.4: CO_2 and NO_2 emission factors from fuel combustion for electricity generation

Fuel	CO2 (e/t)	NO2 (e/kg)
Price	2,0	4,5

Table C.5: CO_2 and NO_2 emission factors from fuel combustion for electricity generation

ID	Min Discharge m^3/s	Max Discharge m^3/s	Initial Reserve Hm^3	Medium Level Hm^3	Upper Level Hm^3	Min Reservoir Hm^3	Max Reservoir Hm^3
Hydro 1	5,00	163,00	80,00	100,00	150,00	6,00	162,00
Hydro 2	14,00	464,00	790,00	500,00	1 000,00	6,00	1 200,00
Hydro 6	14,00	479,00	1 200,00	1 000,00	2 000,00	6,00	2 586,00

Table C.6: Hydro power plants' reservoir characteristics

ID	Piecewise Linearisation				Output Limits			Curves
	$\rho 1_1(i)$	$\rho 1_2(i)$	$\rho 1_3(i)$	U_l	$P0_1(i)$	$P0_2(i)$	$P0_3(i)$	**Spacement**
	$MW/m^3/s$			m^3/s	MW			
Hydro 1	0,40	0,30	0,50	39,50	1,896	2,133	2,370	0,050
Hydro 2	0,20	0,10	0,30	112,50	2,700	3,375	4,050	0,050
Hydro 6	1,30	3,00	1,50	116,250	18,135	18,833	19,530	0,050

Table C.7: Hydro power plants' piecewise linearisation of performance curves

ID	Fabricant	Model	# Turbines
W1	Enercom	E82E2	42
W2	Enercom	E126	13
W3	Enercom	E82E2i	24
W4	Enercom	E70	28
W5	Enercom	E101	20
W6	Enercom	E101	17
W7	Enercom	E44	33
W8	Enercom	E82E2	24

Table C.8: Wind farms' turbines models

ID	Start-Up	Shut-Down	Generation	
	€	€	€	€/MW
Thermal 1	900,00	3 200,00	2 200,00	30,00
Thermal 2	6 600,00	3 200,00	930,50	49,00
Thermal 3	4 800,00	3 200,00	6 500,00	28,00
Thermal 4	780,00	3 200,00	2 400,00	30,00
Thermal 5	4 200,00	3 200,00	130,20	59,50
Thermal 6	7 000,00	3 200,00	900,00	35,00
Hydro 1	150,00	0,00	0,00	64,00
Hydro 2	200,00	0,00	0,00	60,00
Hydro 6	300,00	0,00	0,00	60,00
W1	0,00	0,00	0,00	8,00
W2	0,00	0,00	0,00	5,00
W3	0,00	0,00	0,00	4,00
W4	0,00	0,00	0,00	7,00
W5	0,00	0,00	0,00	8,00
W6	0,00	0,00	0,00	4,50
W7	0,00	0,00	0,00	3,20
W8	0,00	0,00	0,00	4,00

Table C.9: Generation's fixed and variable costs

Time	**Pool Market Clearing Prices**	
	Low Wind Scenario	**High Wind Scenario**
h	€$/MWh$	
00:00	47,65	30,00
01:00	30,00	28,00
02:00	30,00	28,00
03:00	30,00	28,00
04:00	30,00	28,00
05:00	36,97	30,00
06:00	30,00	30,00
07:00	40,15	39,63
08:00	45,13	30,00
09:00	54,50	45,50
10:00	55,00	50,81
11:00	55,00	52,06
12:00	55,00	52,54
13:00	55,00	51,00
14:00	55,00	49,00
15:00	55,00	49,00
16:00	55,00	49,00
17:00	55,00	54,22
18:00	57,00	55,00
19:00	59,38	55,00
20:00	57,50	55,00
21:00	55,00	55,00
22:00	55,00	50,11
23:00	49,00	46,00

Table C.10: Day-ahead pool market clearing prices